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DETAILED FINAL REPORT OF RESEARCH ON
HIGH-SPEED ROTARY-FIXED WING AIRCRAFT

VOLUME II

AIR LOADS ON AN AUTOROTATING ROTOR
AT HIGH TIP SPEED RATIOS

OFFICE OF NAVAL RESEARCH, AMPHIBIOUS BRANCH
PROJECT NR 250-001 CONTRACT N9onr-84901

Report 1775 1 August 1950

Serial No. 37

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Enclosure (2)
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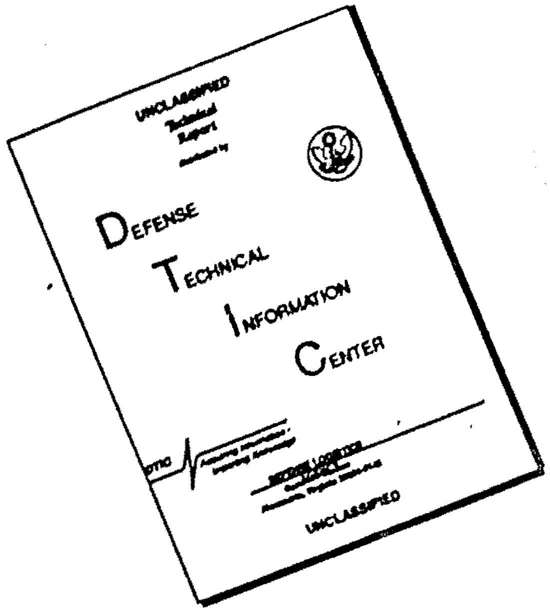

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REPORT 1775

DATE 1 August 1950

REVISED

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DETAILED FINAL REPORT OF RESEARCH ON

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VOLUME II

AIR LOADS ON AN AUTOROTATING ROTOR AT HIGH TIP SPEED RATIOS

SUBMITTED UNDER Contract N9onr-84901 to the Office of Naval Research, Amphibious Branch, Project NR 250-001

PREPARED BY R. E. Head

APPROVED BY K. H. Hohenemser

APPROVED BY

APPROVED BY C. H. Hurkamp

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40. Mean, Maximum and Minimum Blade Torsion Coefficients

2.0 SUMMARY

This report presents the calculated distributions of normal force coefficient, chordwise force coefficient, and torsion moment coefficient about the 25% chord line of an autorotating rotor at zero degrees collective pitch and at high tip-speed ratios ($\mu = 0.5$ to $\mu = 2.0$). These load distributions are a continuation of the determination of the aerodynamic characteristics of a rotor at high tip-speed ratios presented in Reference 1.

This analysis is for a rotor having rectangular, untwisted blades and no tip drag. The effects of reversed flow, blade stall, and tip loss are included. The rotor has the following physical characteristics:

Number of blades, $b = 3$

Blade mass coefficient, $\gamma = \dfrac{\rho a c R^4}{I_b} = 5.0$

Solidity ratio, $\sigma = \dfrac{bc}{\pi R} = .05$

As shown in Reference 1, the coefficients may be considered directly proportional to the solidity ratio and, hence, are applicable to a wide range of rotor solidity ratios.

The coefficients plotted in this report are based on the calculations of Reference 1 and represent the forces or moments on <u>three</u> blades. Therefore, to find the coefficient for one blade, the ordinates of all curves must be divided by three.

3.0 DISCUSSION

3.1 Normal Force (Thrust) Distribution - For Reference 1 the spanwise thrust distributions for twelve azimuth stations were calculated for each of several values of advance ratio, μ; collective pitch, ϑ; and control plane angle of attack, α. The thrust found in this manner is normal to the control plane, but in the special case where the collective pitch is zero degrees with respect to the control plane, the thrust is also normal to the chord-plane of the blade.

The present analysis is for the autorotating rotor with no tip drag included. None of the points calculated for Reference 1 coincides exactly with the autorotation points so an interpolation is made to obtain the autorotation values. The spanwise normal force coefficients are plotted in Figures 2 through 7 for μ values from 0.5 to 2.0. The loading around the azimuth is shown in Figures 8 through 13. An harmonic analysis is made of the azimuthal thrust distribution and the mean and first five harmonics are plotted in Figure 14.

3.2 Chordwise (In-Plane) Force Distribution - The chordwise force was not determined as such in Reference 1 but is easily derived from the torque calculations by dividing the section radius out of the torque coefficient distributions. The force found thus is in the control plane and for this special case where the col-

lective pitch is zero, it is also in the chord-plane. Interpolations to autorotation conditions are made from the calculated values of Reference 1 simultaneously with converting from torque to in-plane force. The spanwise distributions of the chordwise force coefficient are plotted in Figures 15 through 20; the loading around the azimuth is shown in Figures 21 through 26. An harmonic analysis is made of the azimuthal chordwise force distribution and the mean and first five harmonics are plotted in Figure 27.

3.3 Torsion Moment Distribution - The torsion moment coefficients are found by multiplying the normal force coefficients found in Section 3.1 by the chordwise distance from the quarter-chord point to the center of pressure. The center of pressure location at section angles of attack from 0° to 180° is given in Figure 1 which is taken directly from Reference 2. The section angles of attack of the rotor are interpolated from Reference 1. The spanwise distributions of the torsion coefficient are plotted in Figures 28 through 33 and the loading around the azimuth are given in Figures 34 through 32.

The torsion coefficients found above are in the rotating rotor system. They are converted into appropriate vertical components and components about the longitudinal and lateral axes in the non-rotating system to which the helicopter rotor controls are

attached. The mean, maximum and minimum values of these components as well as the mean, maximum and minimum values of the torsion coefficients of one blade are given in Figure 40

4.0 EQUATIONS

The normal force coefficient, chordwise force coefficient, and torsional moment coefficient are defined, respectively, in the following manner:

$$C_T = \frac{T}{\rho \pi R^2 (\Omega R)^2} \tag{1}$$

$$C_P = \frac{P}{\rho \pi R^2 (\Omega R)^2} \tag{2}$$

$$C_\tau = \frac{\tau}{\rho c \pi R^2 (\Omega R)^2} \tag{3}$$

Where:

T = normal force
P = chordwise force
τ = torsion about the quarter-chord line of the blade
R = rotor radius
c = blade chord
Ω = rotational speed of the rotor

The conversion of the blade torsion from the rotating to the non-rotating coordinate system is:

Component about longitudinal axis:

$$C'_\tau = \frac{1}{3}\left[C_{\tau_r} \sin\psi + C_{\tau_{(\psi+120)}} \sin(\psi+120^\circ) + C_{\tau_{(\psi+240)}} \sin(\psi+240^\circ)\right] \tag{4}$$

Component about lateral axis:

$$C''_\tau = \frac{1}{3}\left[C_{\tau_r} \cos\psi + C_{\tau_{(\psi+120)}} \cos(\psi+120^\circ) + C_{\tau_{(\psi+240)}} \cos(\psi+240^\circ)\right] \tag{5}$$

The vertical component is the sum of Equations (4) and (5).

5.0 REFERENCES

1. Hood, R. [illegible].: Results of An Analytical Study of Aerodynamic Rotor Characteristics at High Tip-Speed Ratios. MAC Report No. 168[illegible], 12 May 1950.

2. Pope, Alan: The Forces and Pressures Over An NACA 0015 Airfoil through 180 Degrees Angle of Attack. Daniel Guggenheim School of Aeronautics, Georgia School of Technology Report No. E-102, February, 1947.

FIGURE 1

EFFECT OF ANGLE OF ATTACK ON THE CHORDWISE LOCATION OF THE CENTER OF PRESSURE

NACA 0015 AIRFOIL
IAS = 80 MPH
RNe = 1,230,000

FROM REFERENCE 2, PAGE 2.006

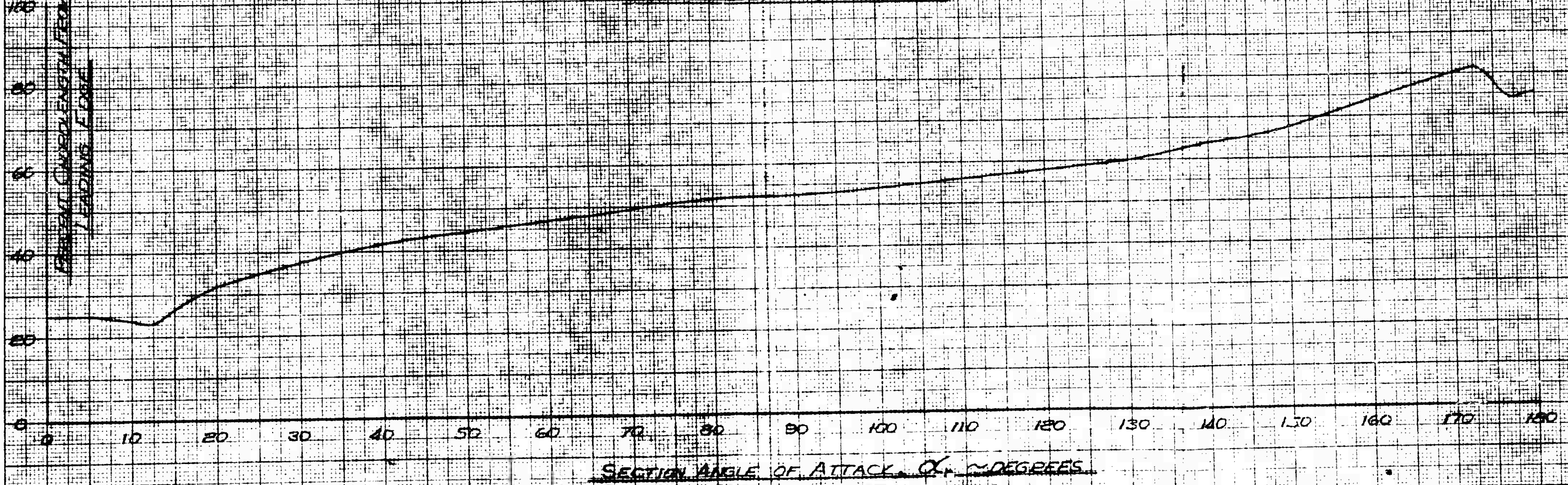
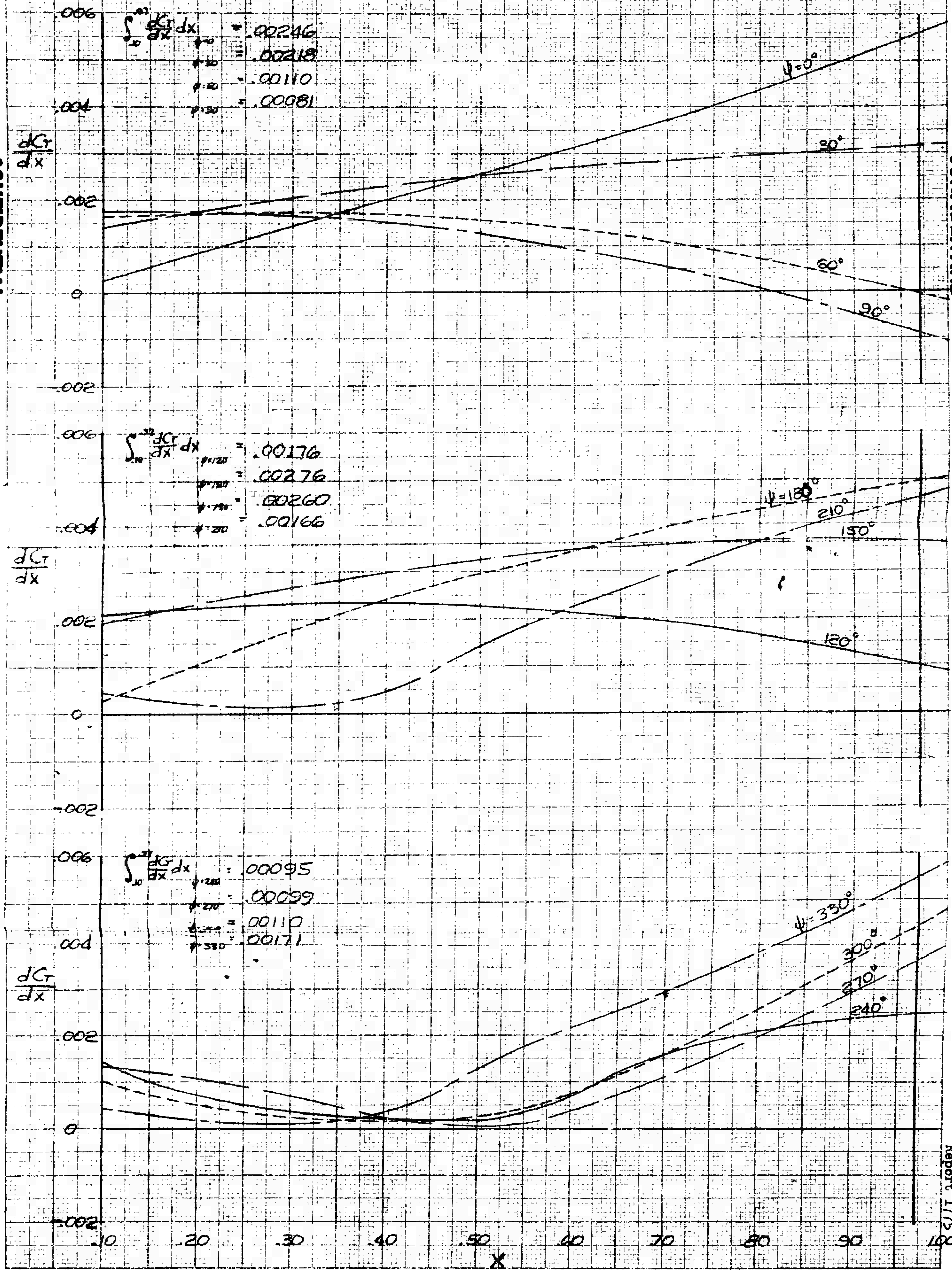


FIGURE 2
THRUST DISTRIBUTION
AUTOROTATION
$\mu = 0.5$
$i = 0°$



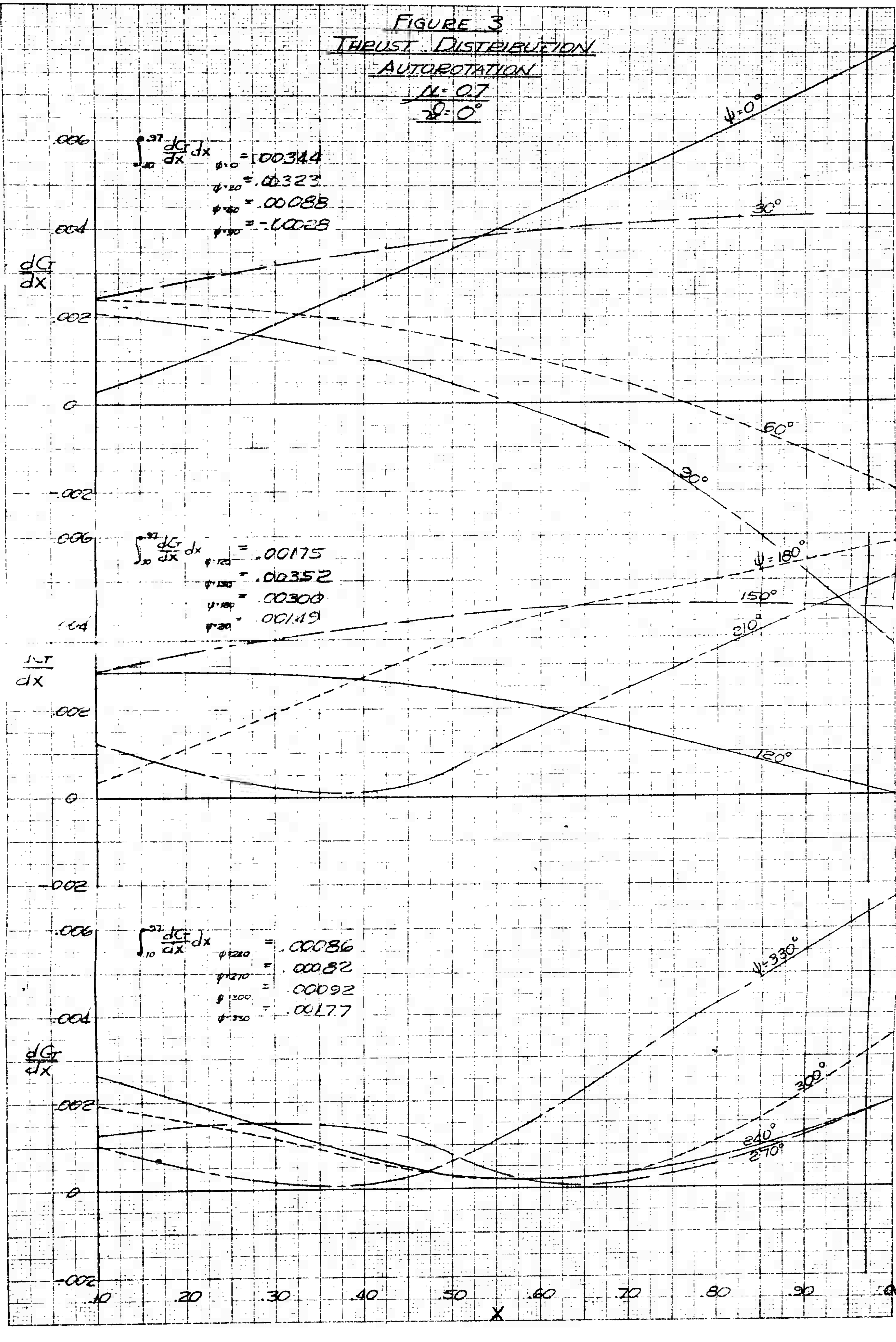


FIGURE 3
THRUST DISTRIBUTION
AUTOROTATION
$\mu = 0.7$
$\theta = 0°$

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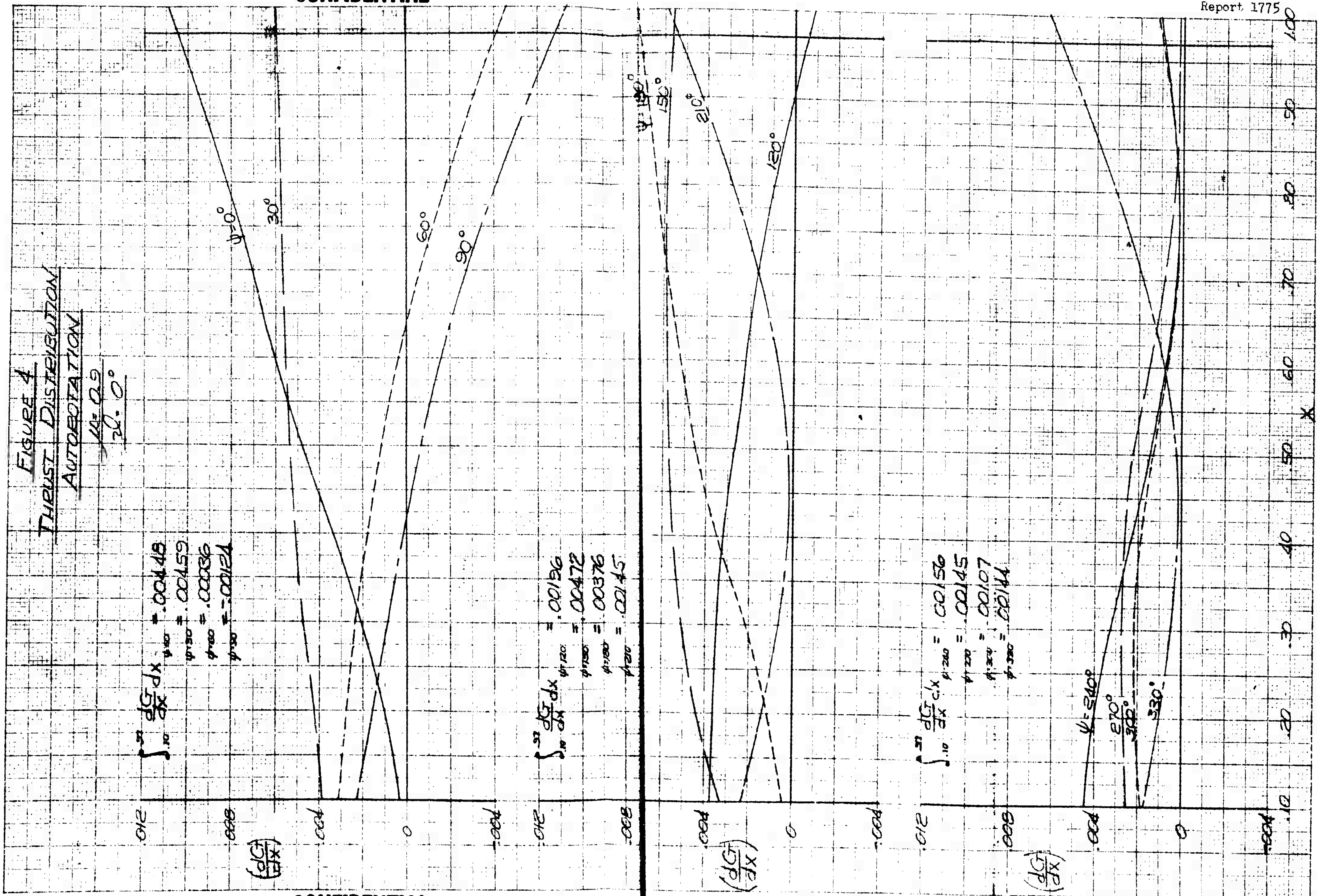

Figure 4
Thrust Distribution
Autorotation
$\mu = 0.5$
$\alpha = 0°$

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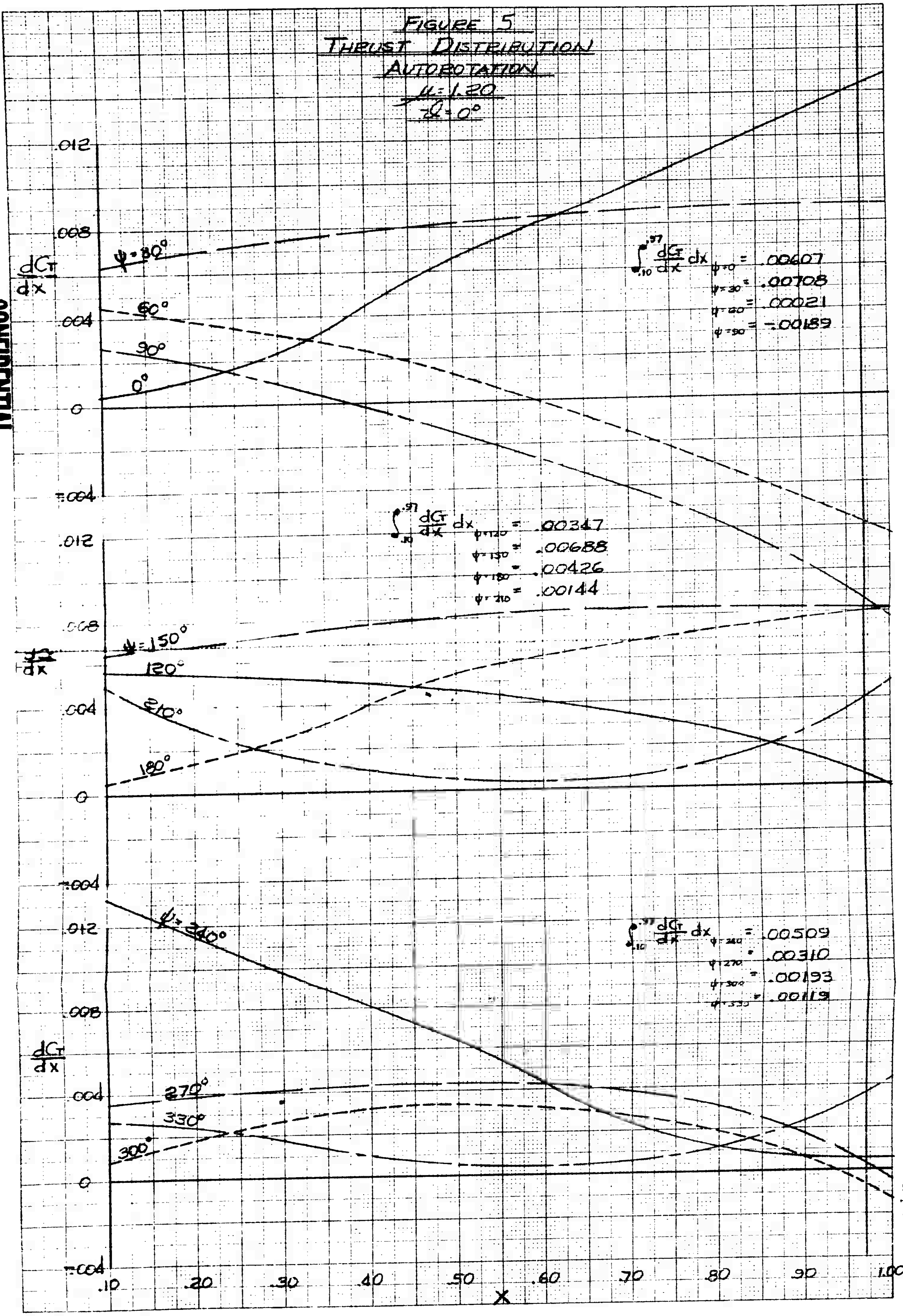

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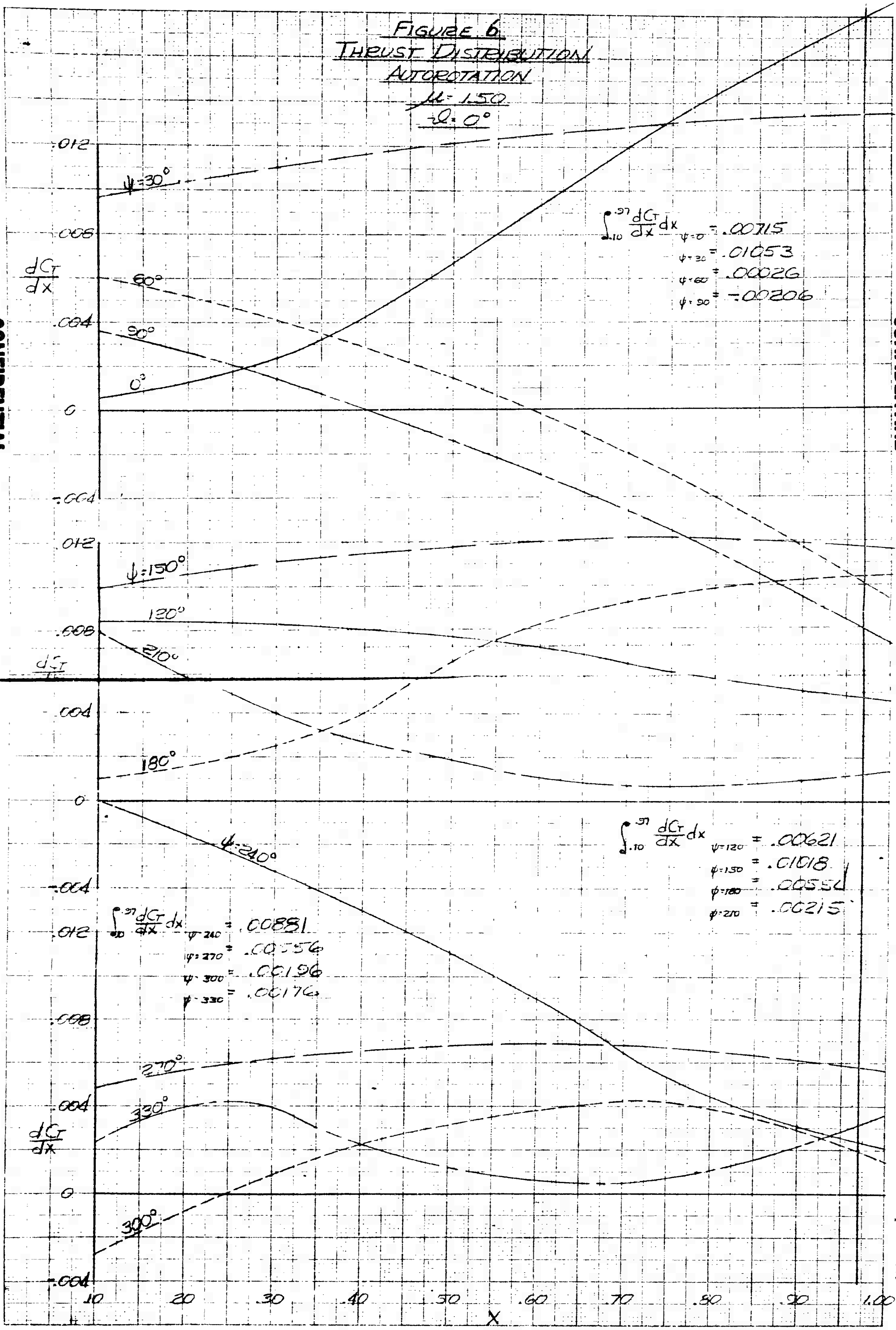

FIGURE 6
THRUST DISTRIBUTION
AUTOROTATION
$\mu = 1.50$
$\theta = 0°$

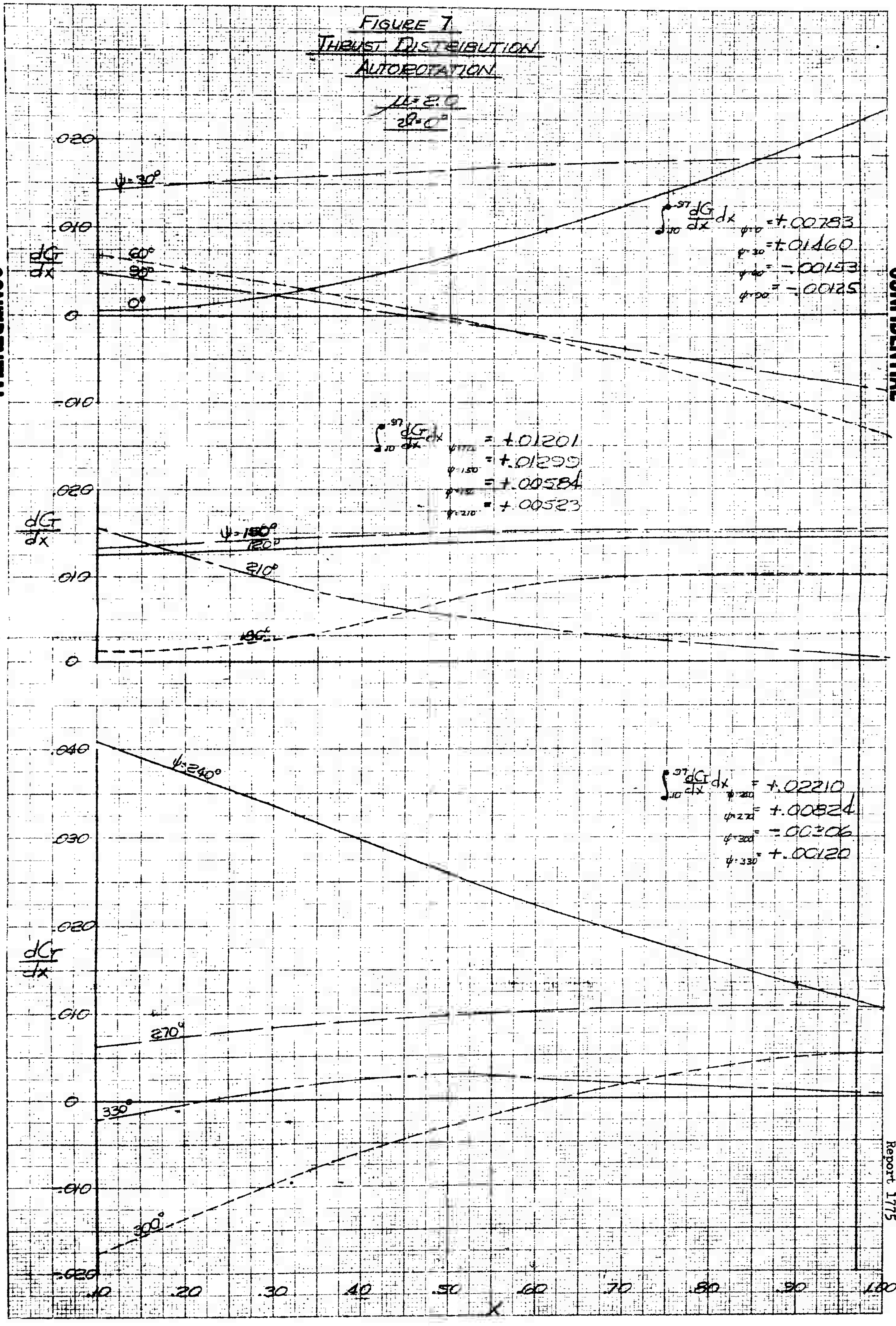

FIGURE 7
THRUST DISTRIBUTION
AUTOROTATION

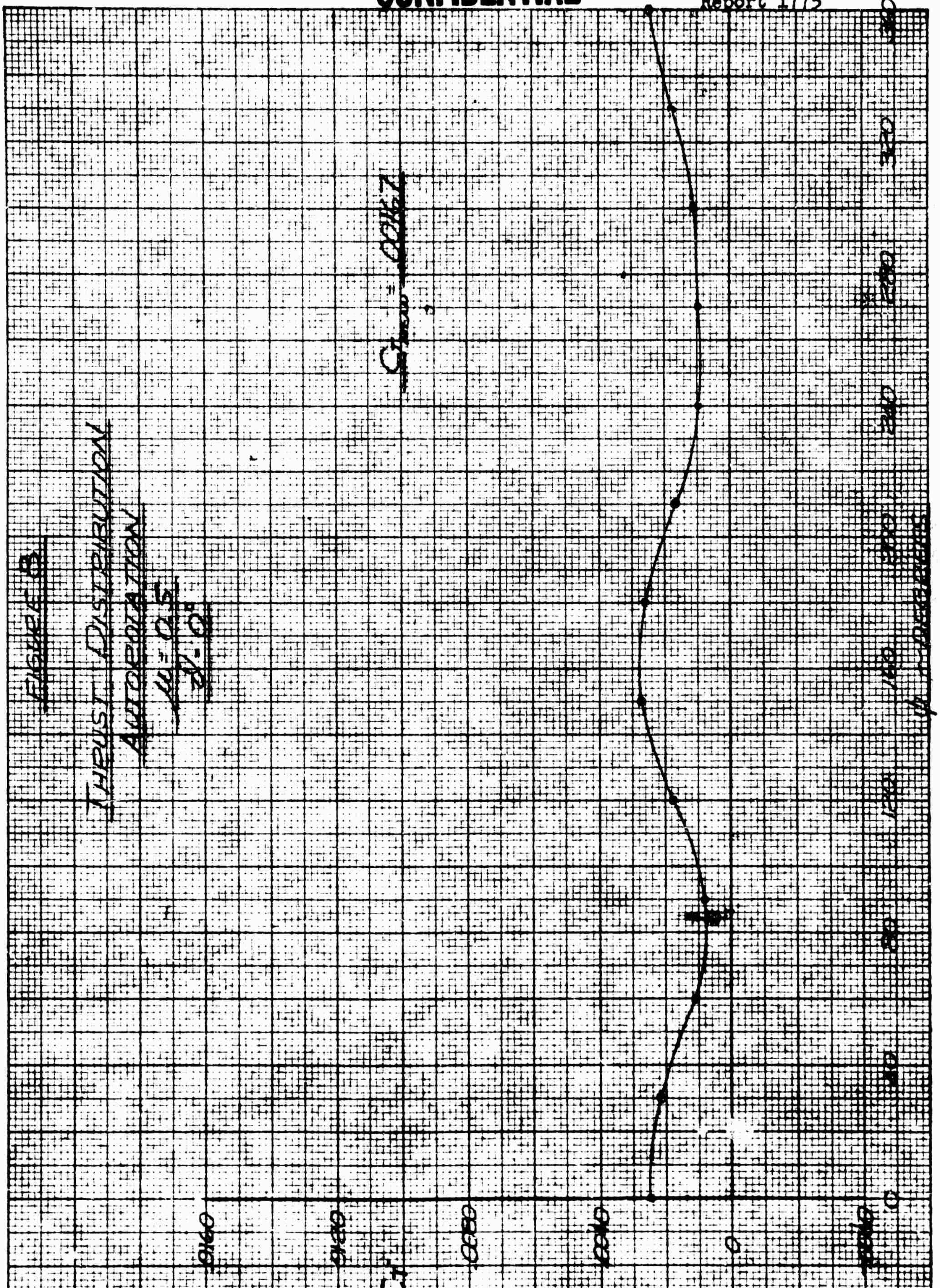
FIGURE 8
THRUST DISTRIBUTION
AUTOROTATION
μ = 0.5
ψ DEGREES
0
40
80
120
160
200
240
280
320
360

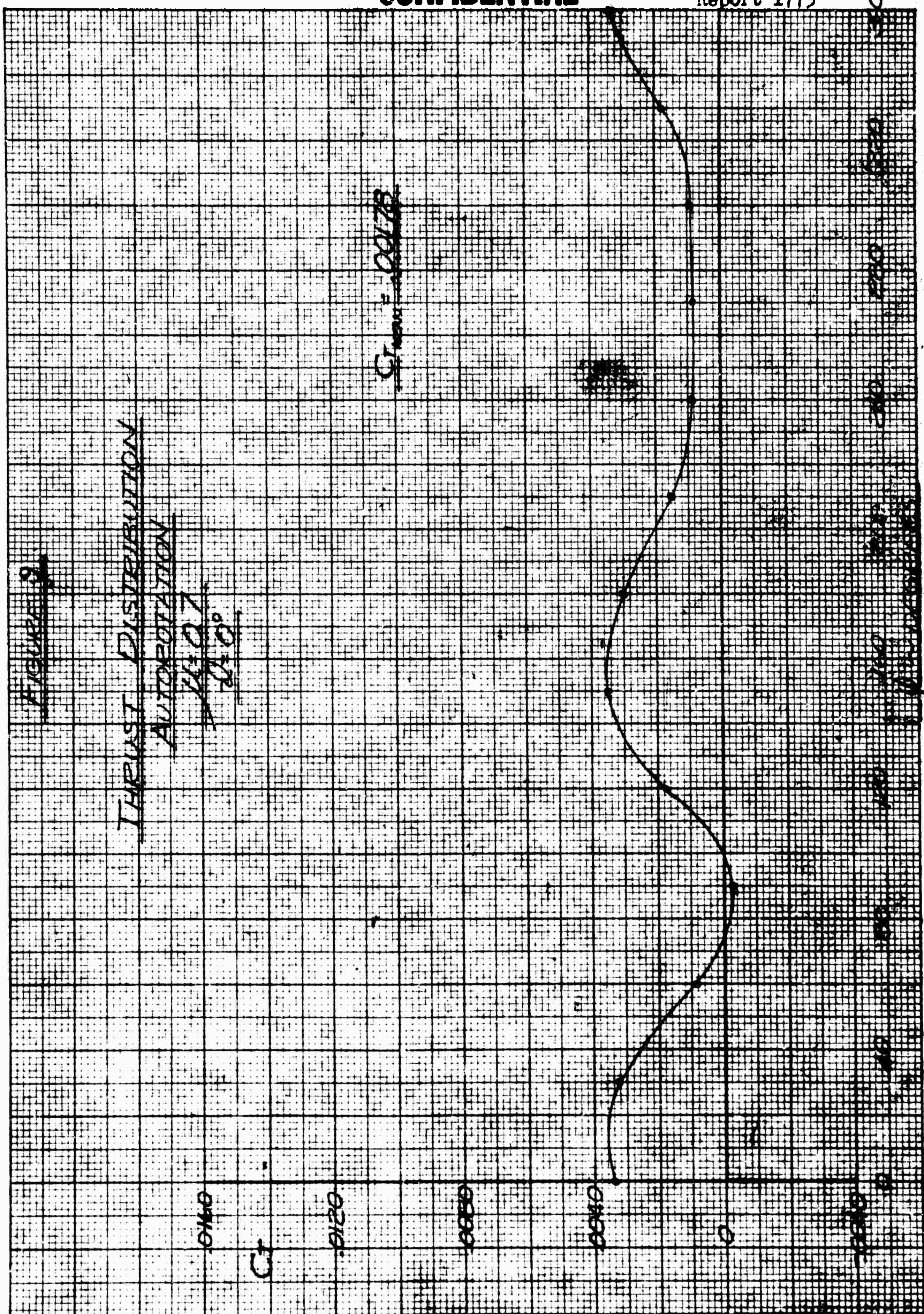
FIGURE 9
THRUST DISTRIBUTION
AUTOROTATION
μ=0.7
α=0°
C_T mean = .00178
C_T
.0160
.0120
.0080
.0040
0
-.0040
0
40
80
120
160
200
240
280
320
360
ψ - DEGREES

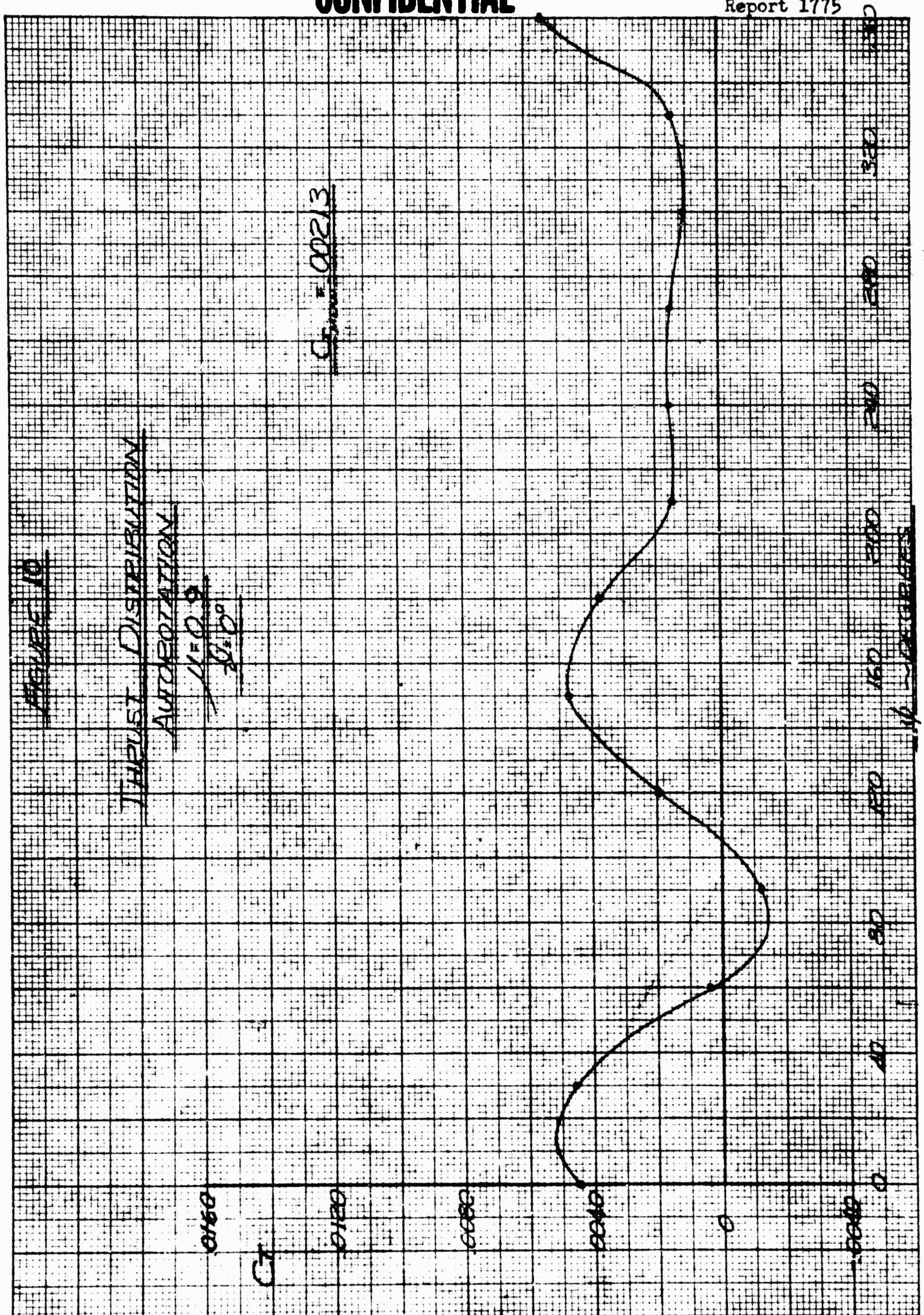
FIGURE 10
THRUST DISTRIBUTION
AUTOROTATION
μ = 0.9
C_T = .00213
ψ ~ DEGREES
C_T
.0160
.0120
.0080
.0040
0
-.0040
0
40
80
120
160
200
240
280
320
360

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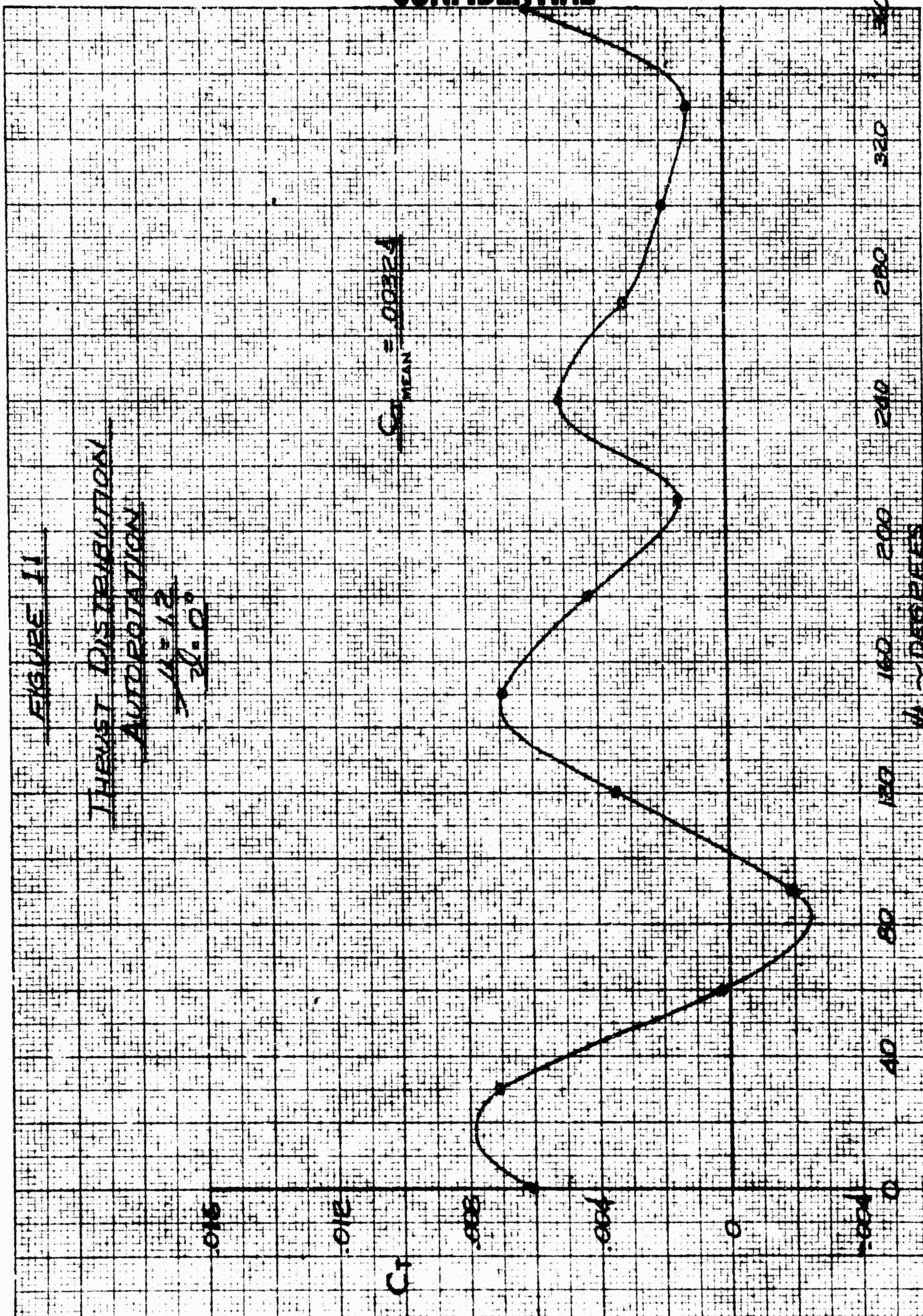

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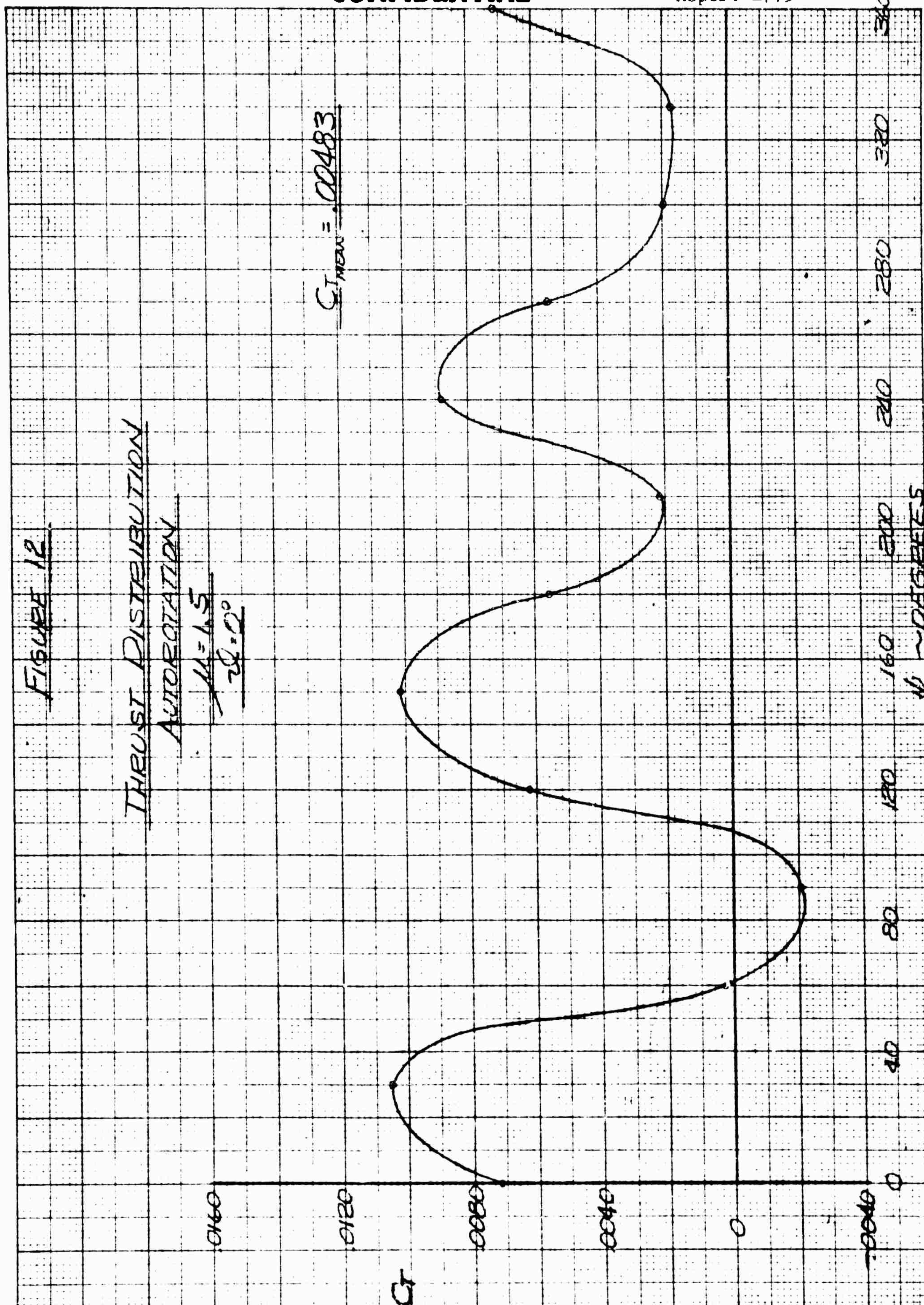
FIGURE 12
THRUST DISTRIBUTION
AUTOROTATION
μ = 1.5
α = 2°
$C_{T_{MEAN}}$ = .00483
ψ ~ DEGREES
C_T
.0160
.0120
.0080
.0040
0
-.0040
0
40
80
120
160
200
240
280
320
360

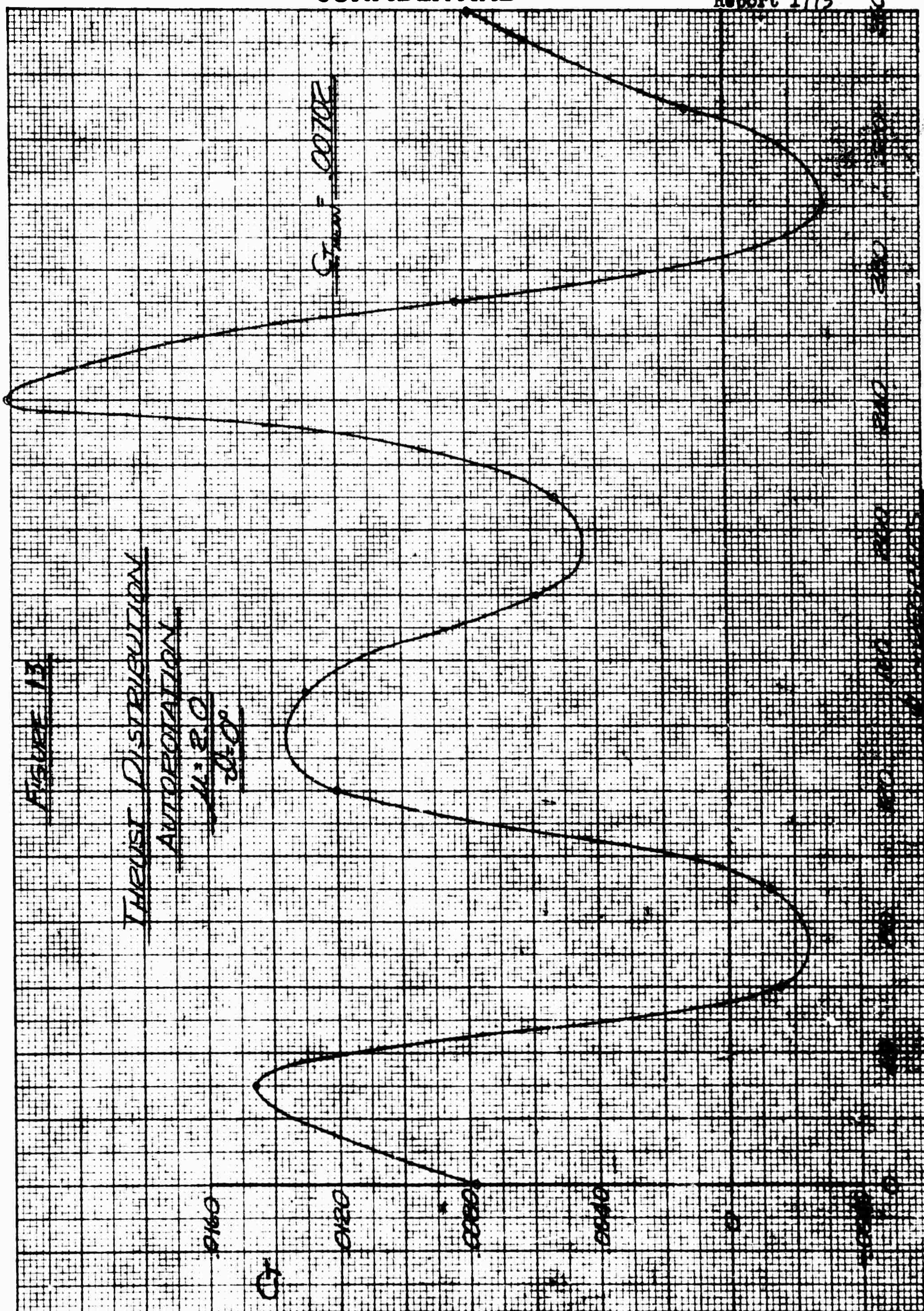
FIGURE 13
THRUST DISTRIBUTION
AUTOROTATION
μ=.20
α=0°
C_T mean = .00702
.0160
.0120
.0080
.0040
0
C_T
120
160
200
240
280
320
360

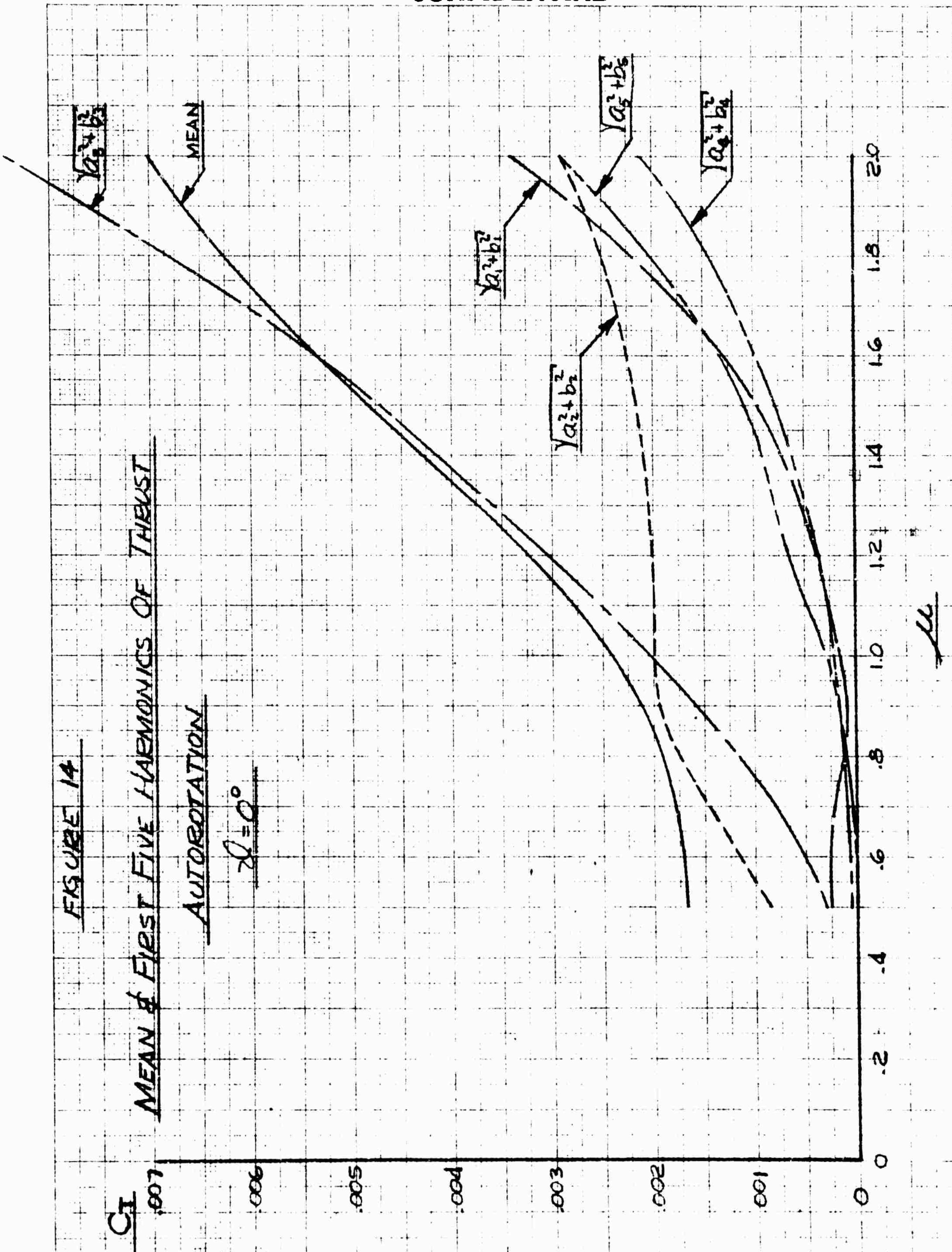
FIGURE 14
MEAN & FIRST FIVE HARMONICS OF THRUST
AUTOROTATION
α = 0°
C_T
.007
.006
.005
.004
.003
.002
.001
0
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
μ
MEAN
√(a₁²+b₁²)
√(a₂²+b₂²)
√(a₃²+b₃²)
√(a₄²+b₄²)
√(a₅²+b₅²)

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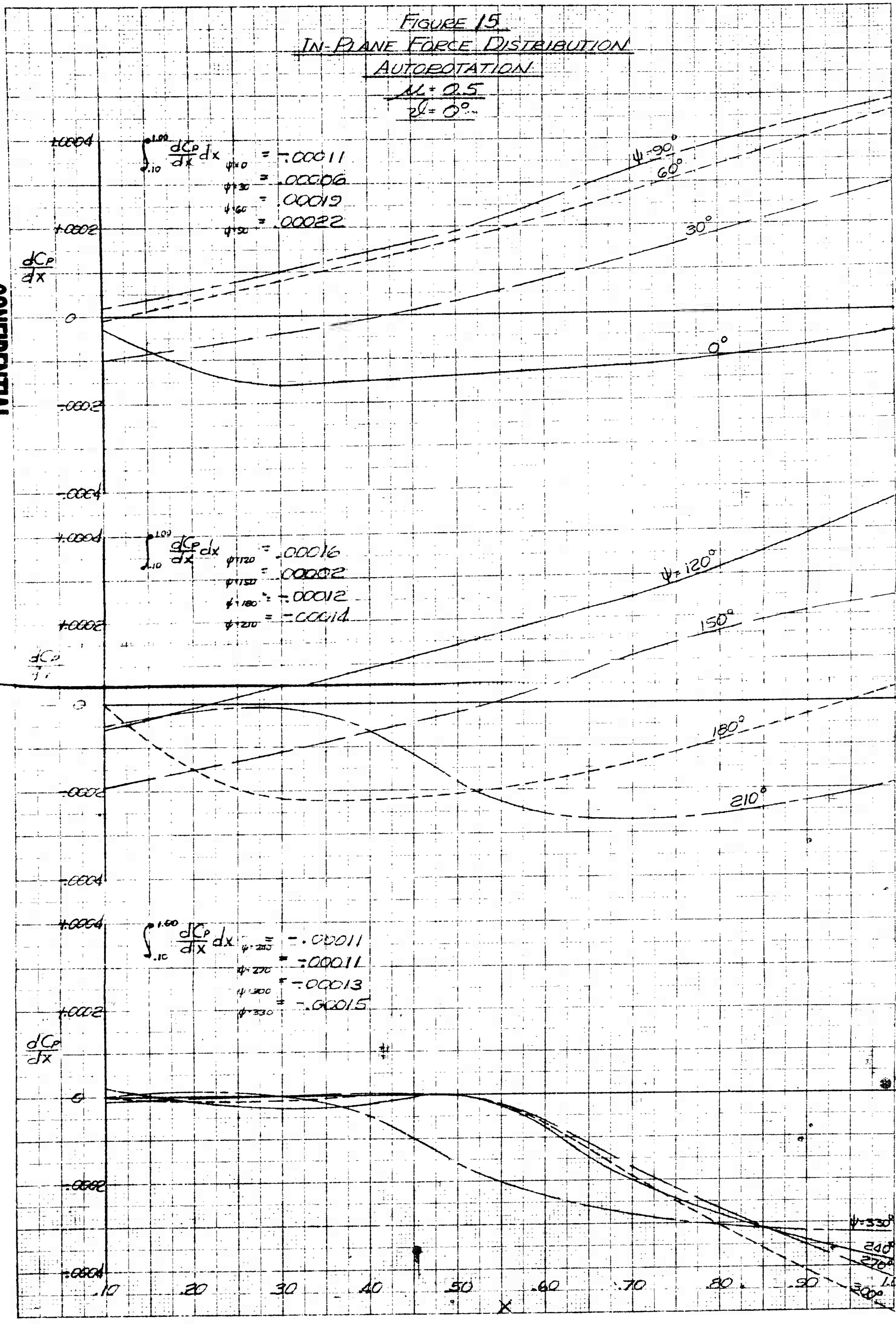

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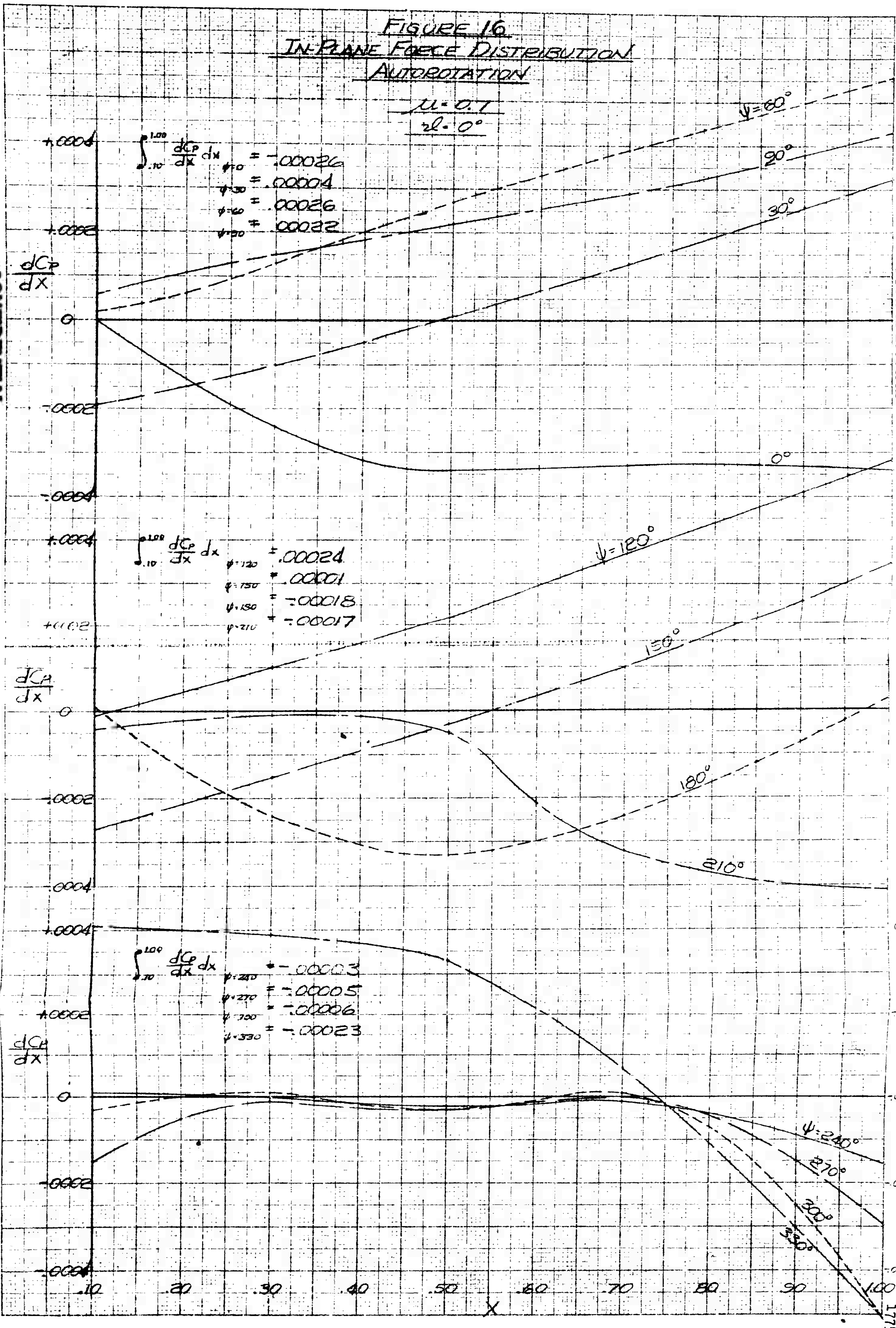
FIGURE 16
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
μ = 0.7
θ = 0°
∫.10^1.00 dCP/dx dx
ψ=0 = -.00026
ψ=30 = .00004
ψ=60 = .00026
ψ=90 = .00032
∫.10^1.00 dCP/dx dx
ψ=120 = .00024
ψ=150 = .00001
ψ=180 = -.00018
ψ=210 = -.00017
∫.10^1.00 dCP/dx dx
ψ=240 = -.00003
ψ=270 = -.00005
ψ=300 = -.00006
ψ=330 = -.00023
ψ=60°
90°
30°
0°
ψ=120°
150°
180°
210°
ψ=240°
270°
300°
330°
dCP/dx
X
+.0004
+.0002
0
-.0002
-.0004
.10
.20
.30
.40
.50
.60
.70
.80
.90
1.00
SCALE FOR ψ = 330° ONLY
-.0002
-.0004
-.0006
-.0008

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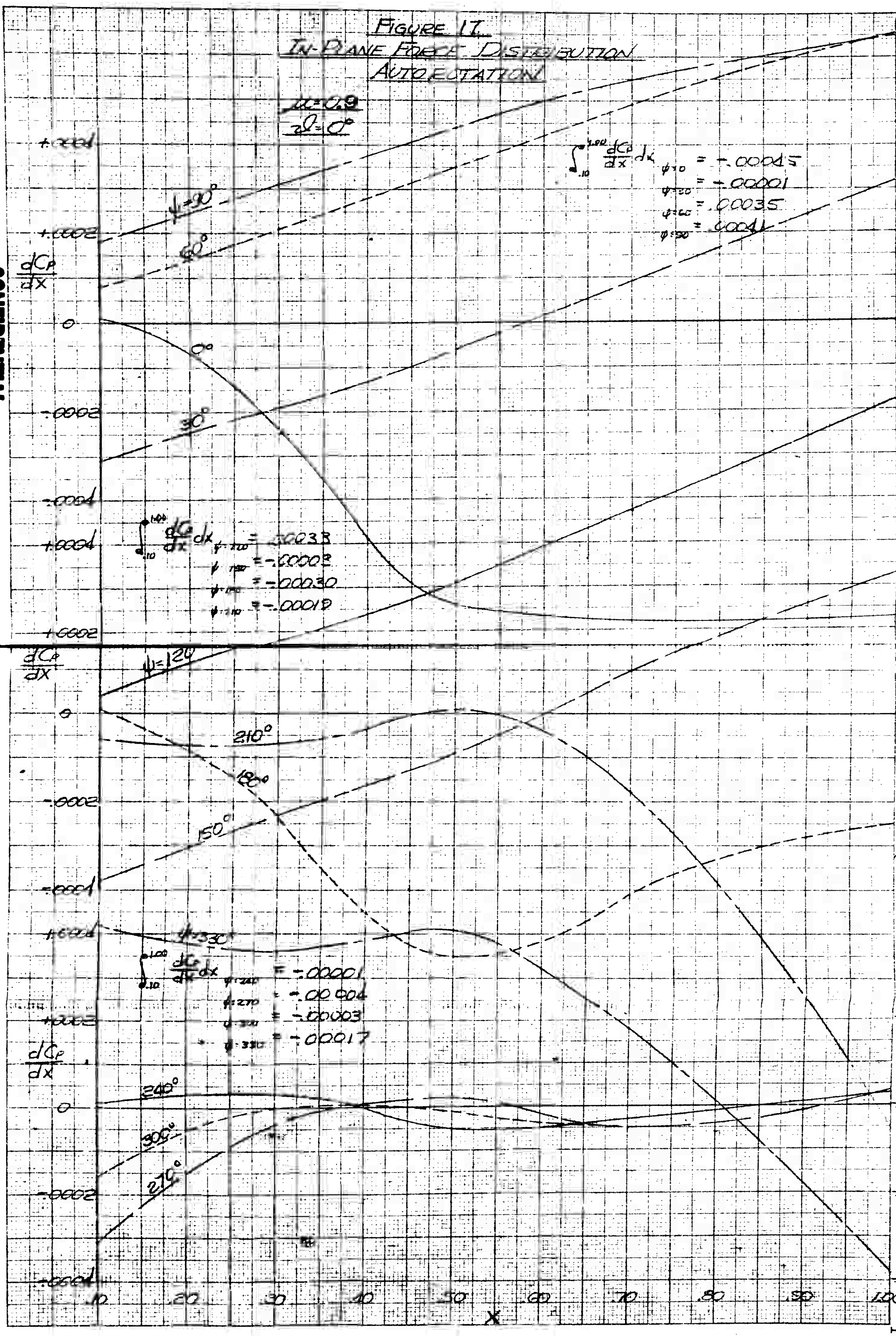

FIGURE 17.
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION

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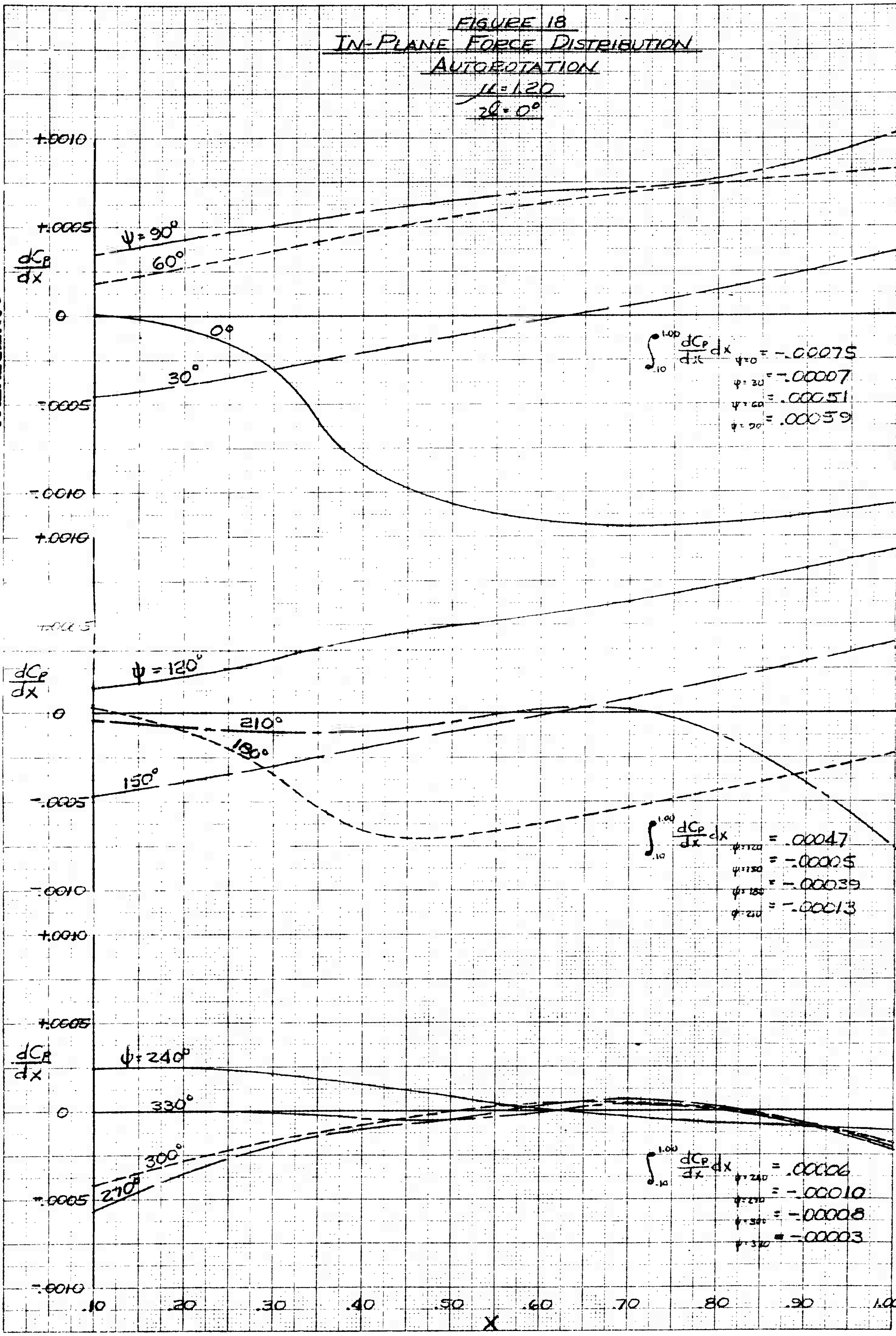

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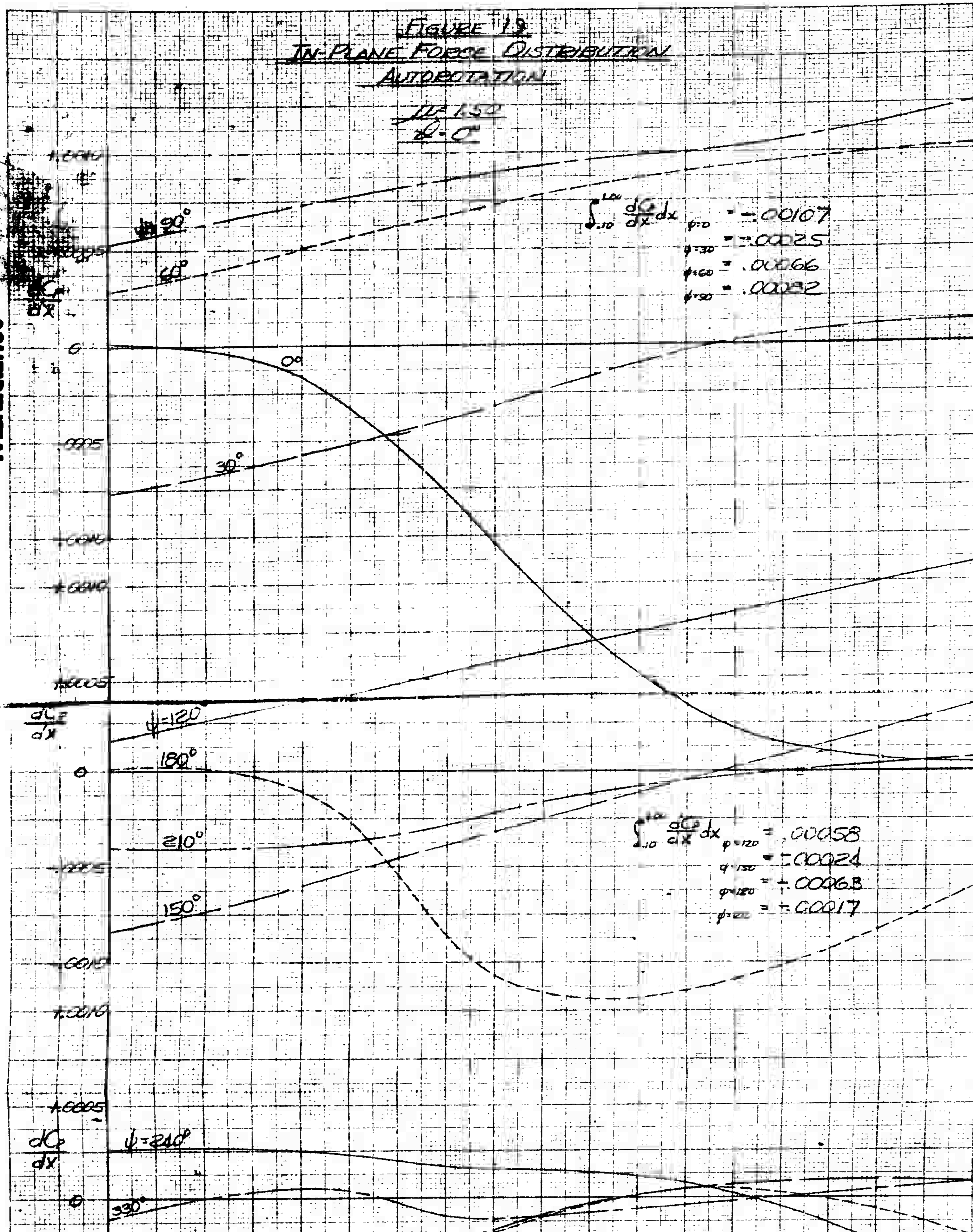

FIGURE 19
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION

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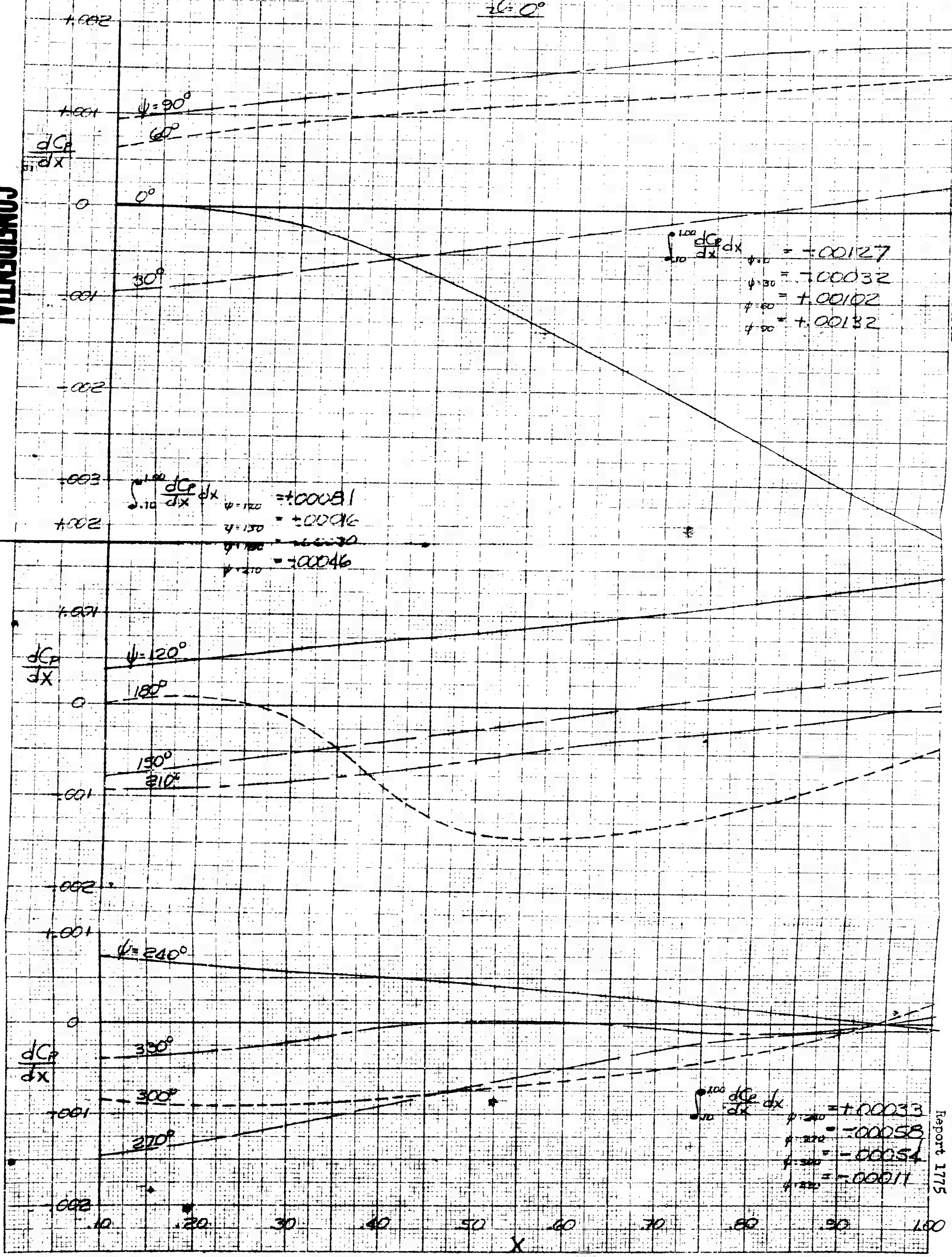
FIGURE 20
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
$\mu = .20$
$i_c = 0°$



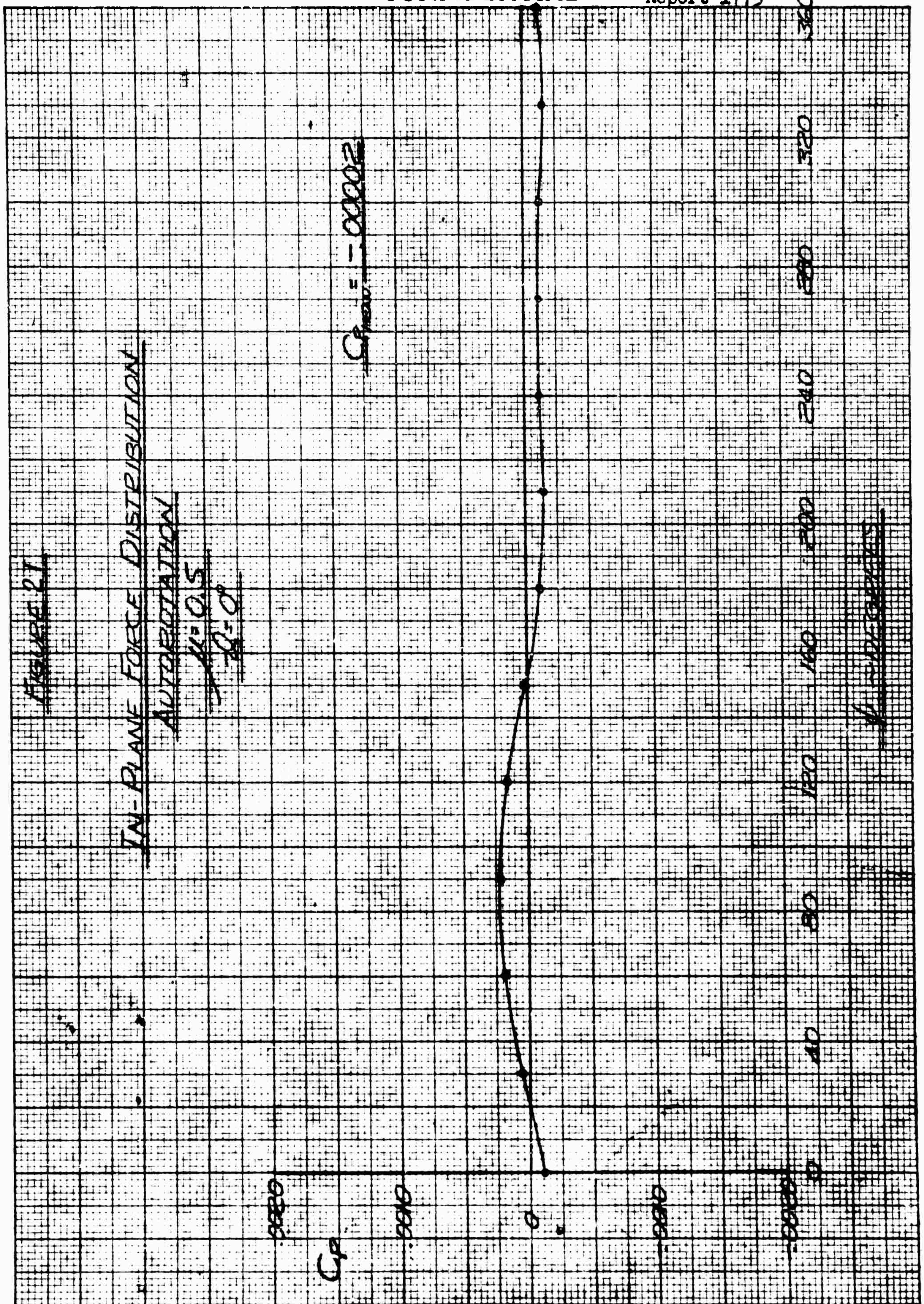


FIGURE 21
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
μ=0.5
α=0°
$C_{P_{MEAN}}$ = -.0002
C_P
.0020
.0010
0
-.0010
-.0020
0
40
80
120
160
200
240
280
320
360
ψ ~ DEGREES

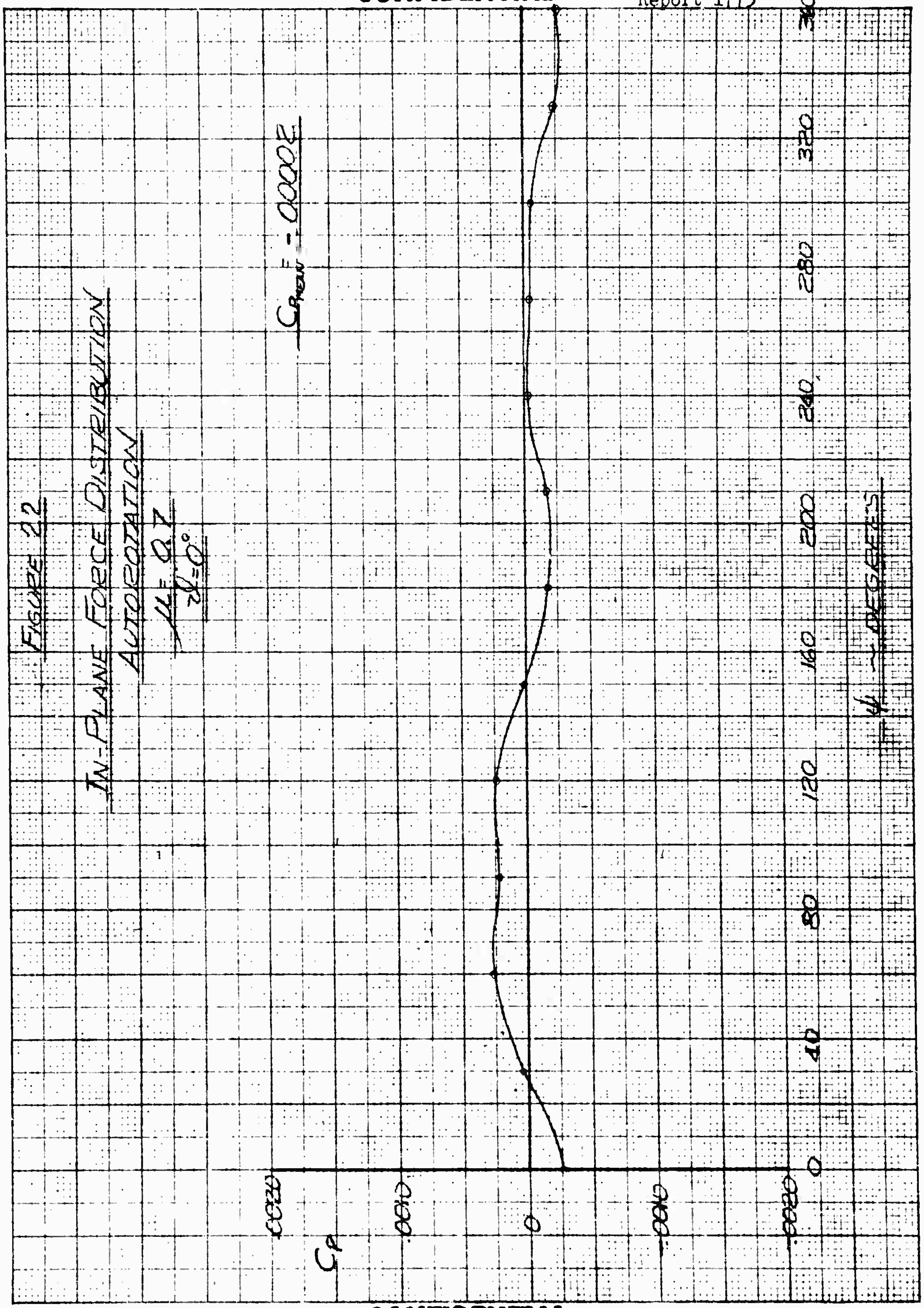
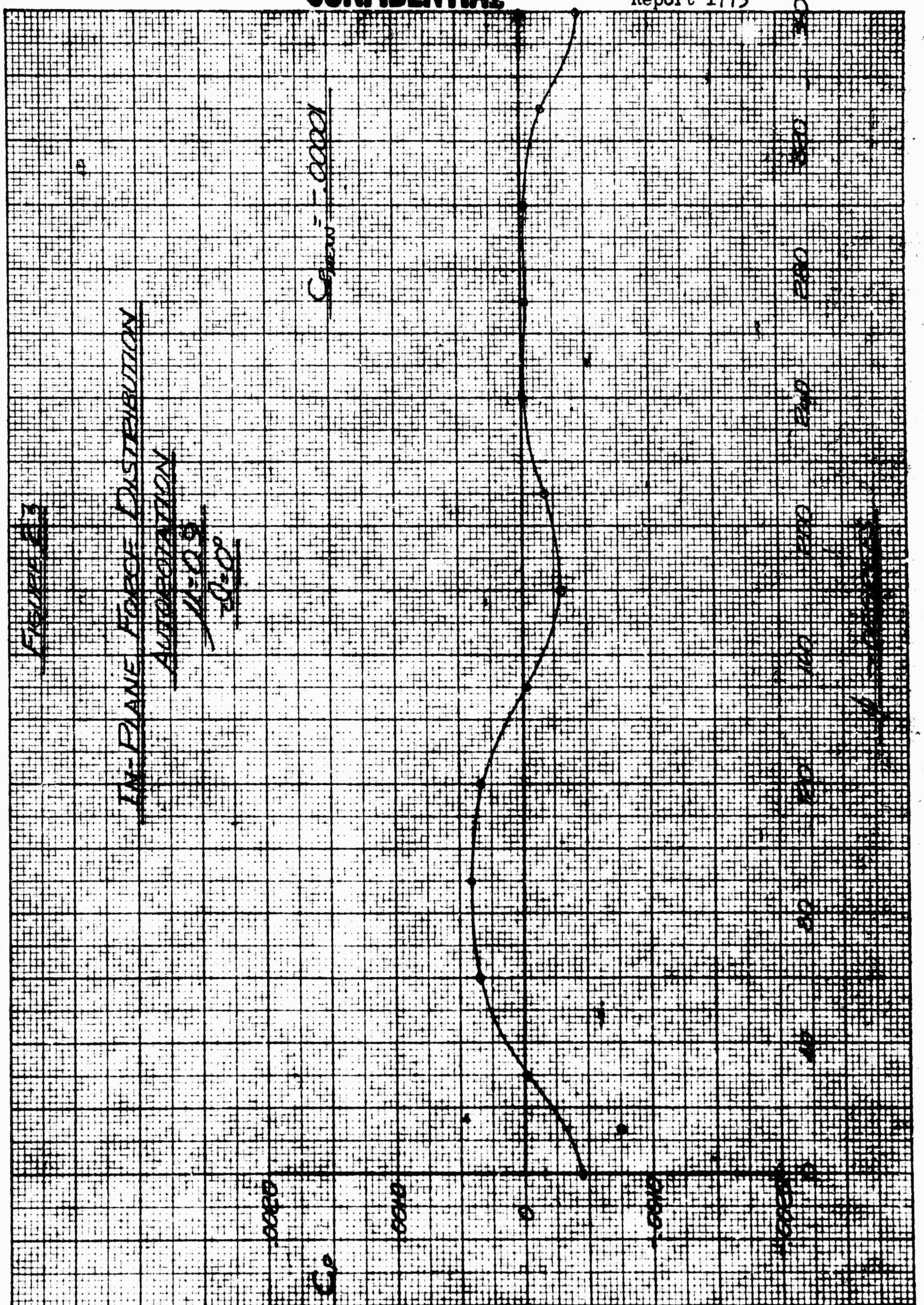


FIGURE 22
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
μ = 0.7
$C_{P_{MEAN}}$ = -.00002
ψ ~ DEGREES
0
40
80
120
160
200
240
280
320
360
C_P
.0020
.0010
0
-.0010
-.0020


IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
0
40
80
120
160
200
240
280
320
360

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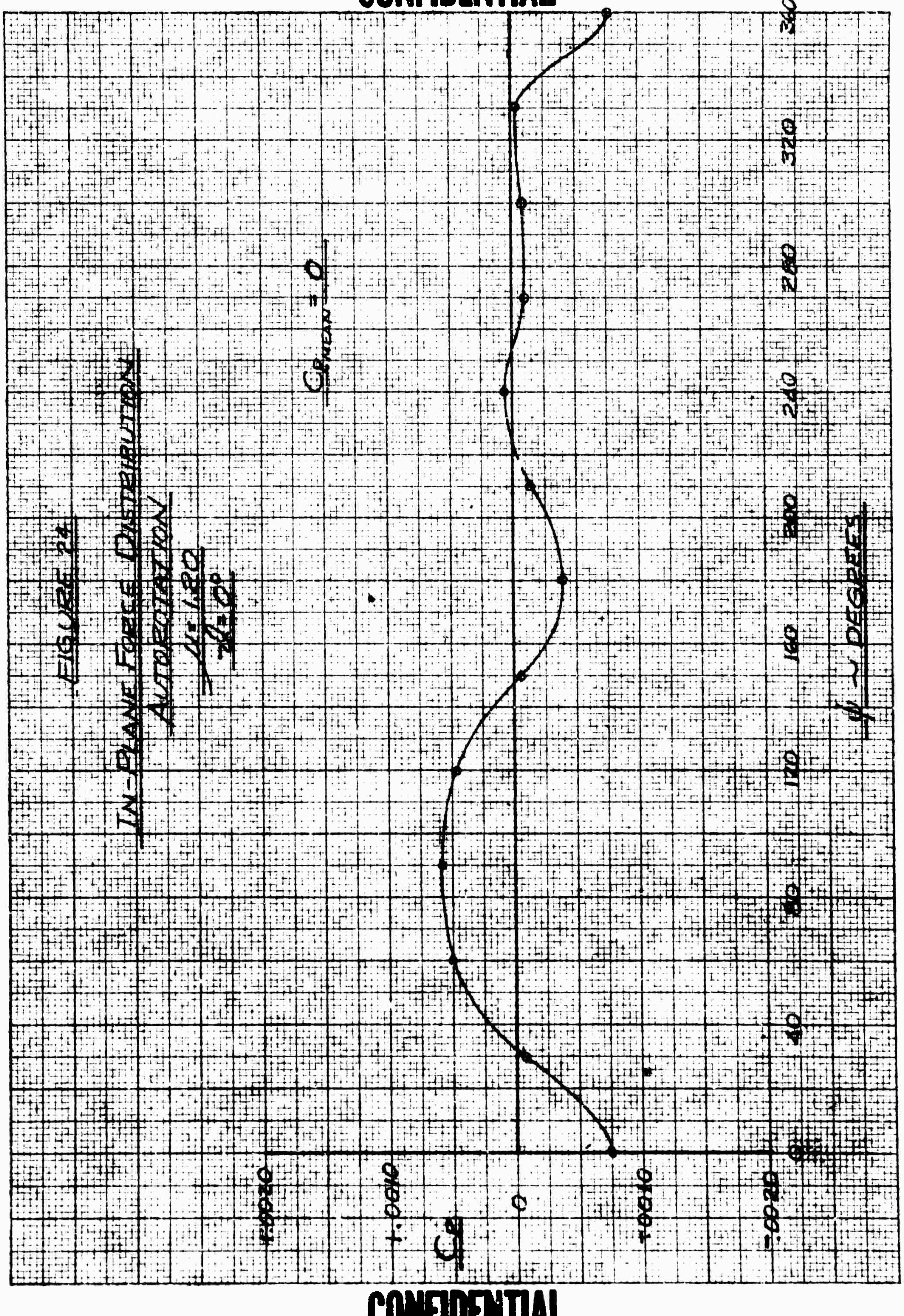

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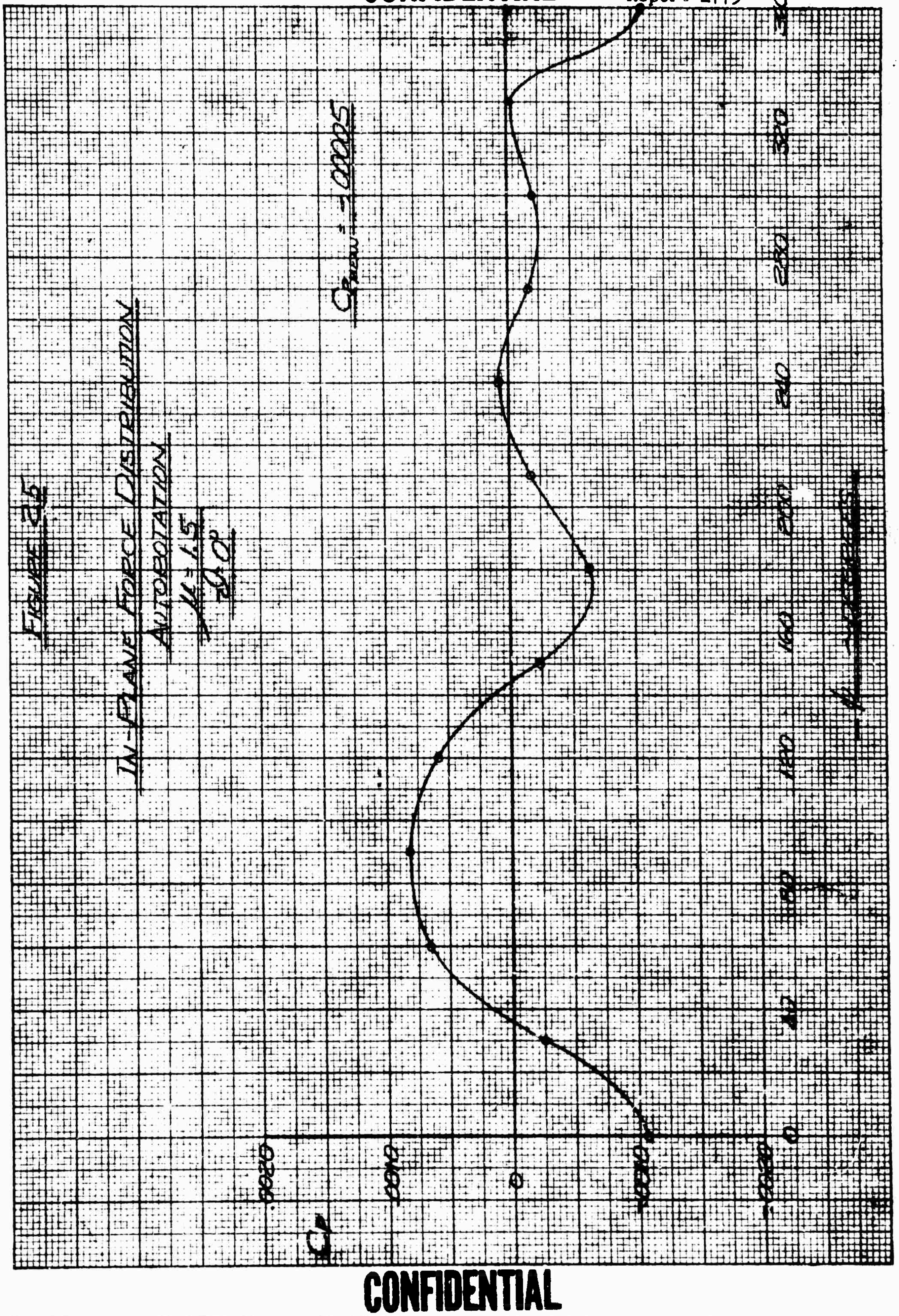
FIGURE 25
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
μ = 1.5
α = 0°
C_F MEAN = -.00005
.0020
.0010
0
-.0010
-.0020
0
40
80
120
160
200
240
280
320
360

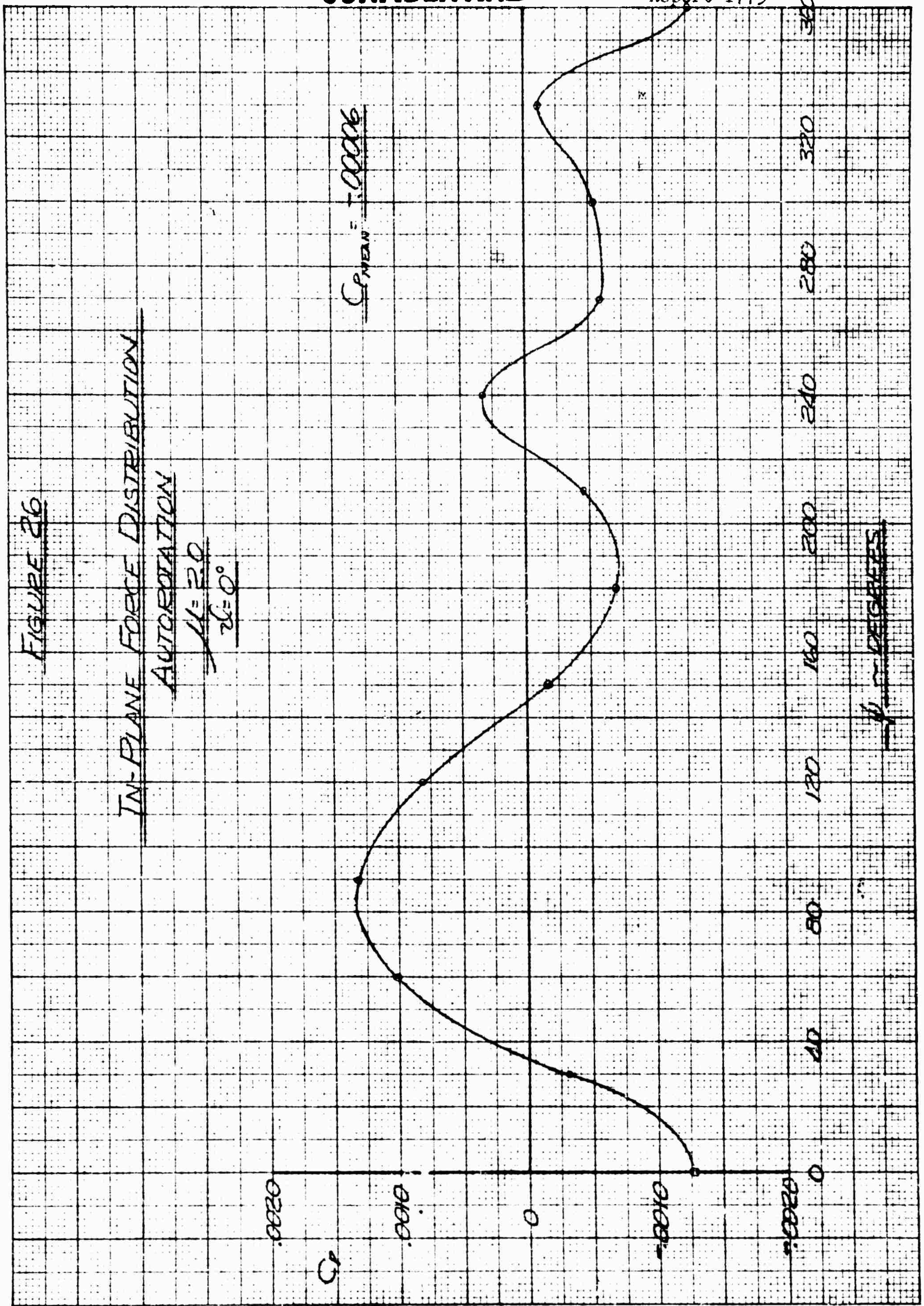
FIGURE 26
IN-PLANE FORCE DISTRIBUTION
AUTOROTATION
μ=.20
α=0°
C_F MEAN = -.0006
ψ ~ DEGREES
C_F
.0020
.0010
0
-.0010
-.0020
0
40
80
120
160
200
240
280
320
360

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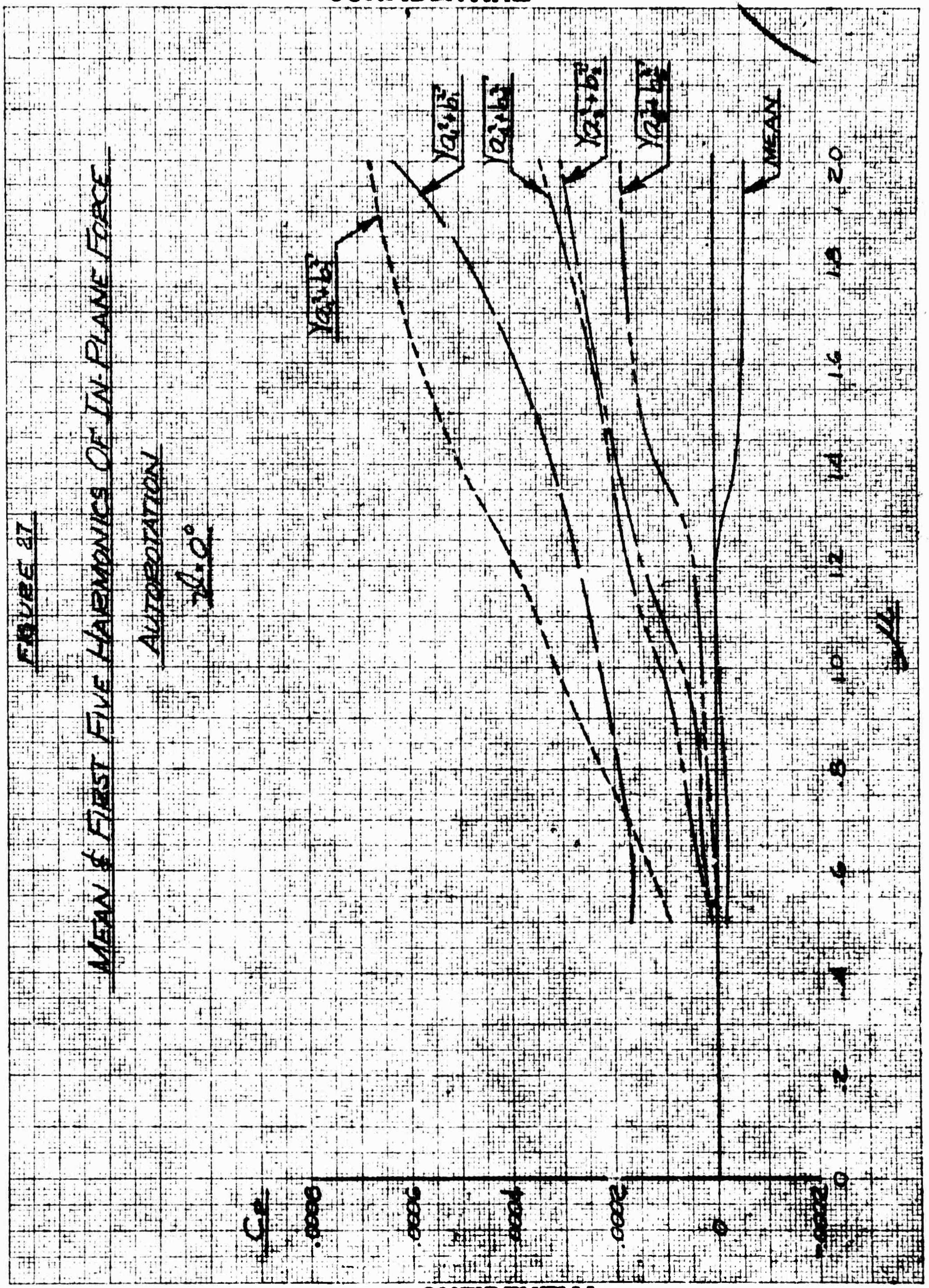

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FIGURE 28
TORSION DISTRIBUTION
AUTOROTATION
$\mu = 0.5$
$\alpha = 0°$

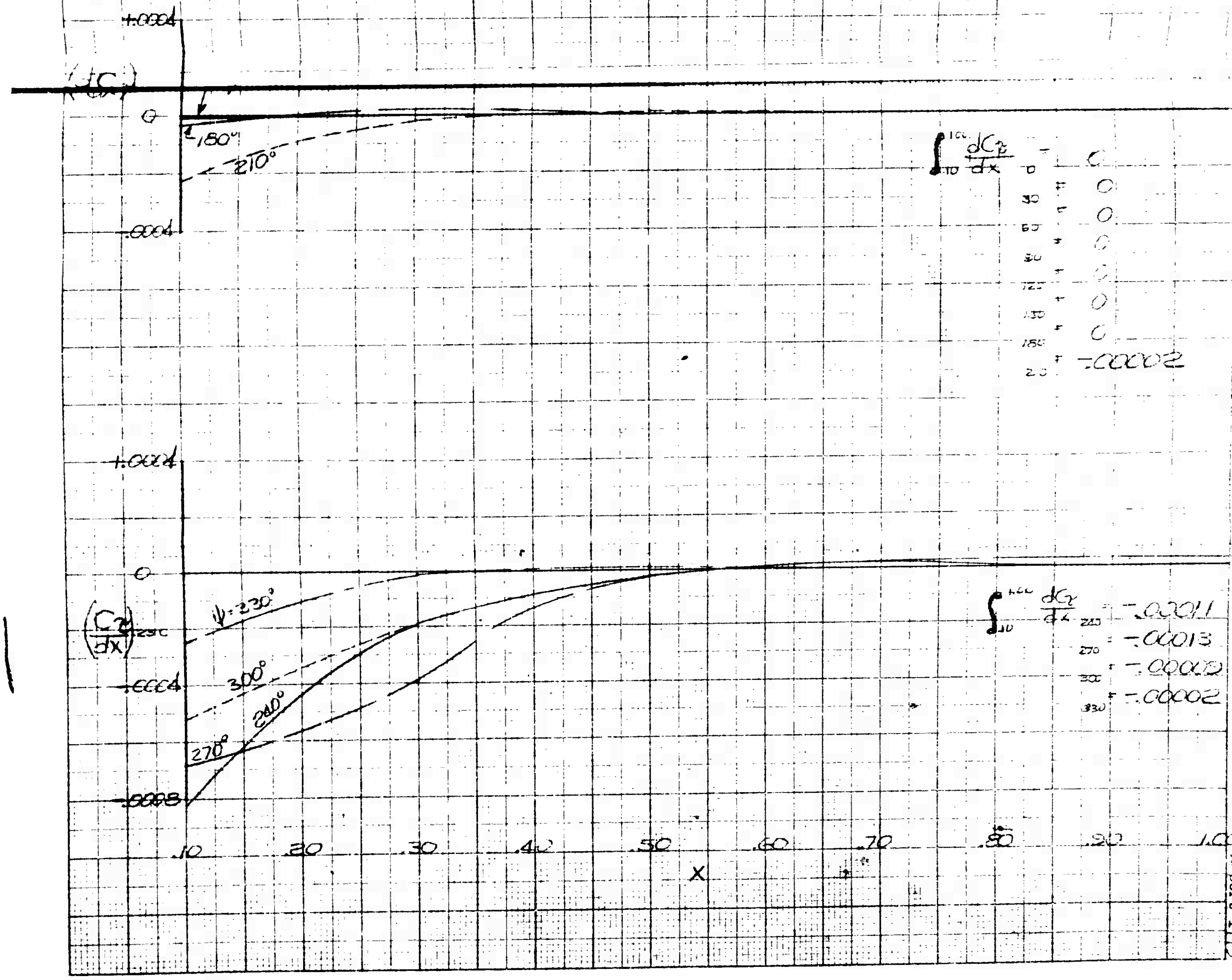

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FIGURE 29
TORSION DISTRIBUTION
AUTOROTATION
$\mu = 0.7$
$\alpha_c = 0°$

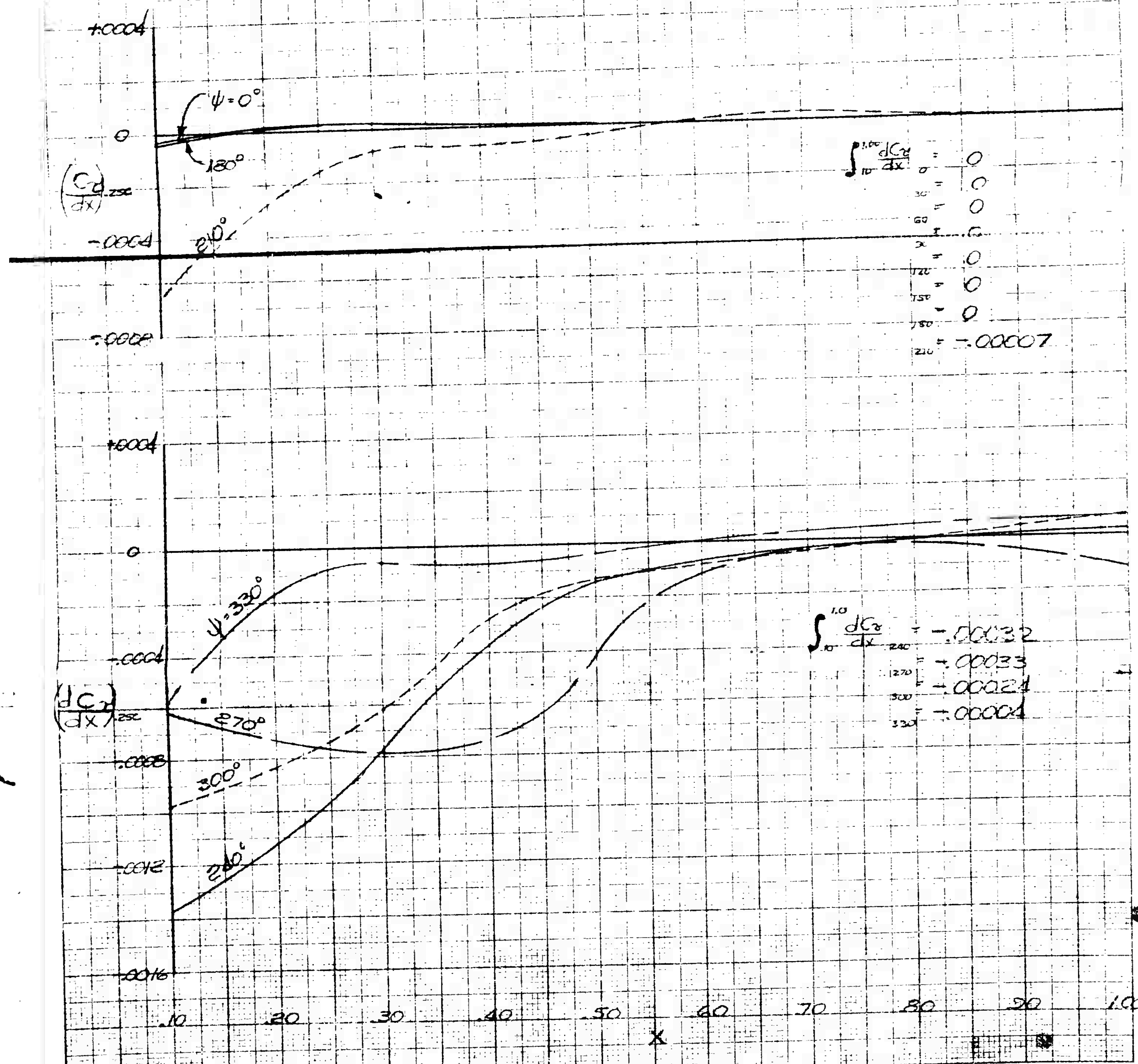
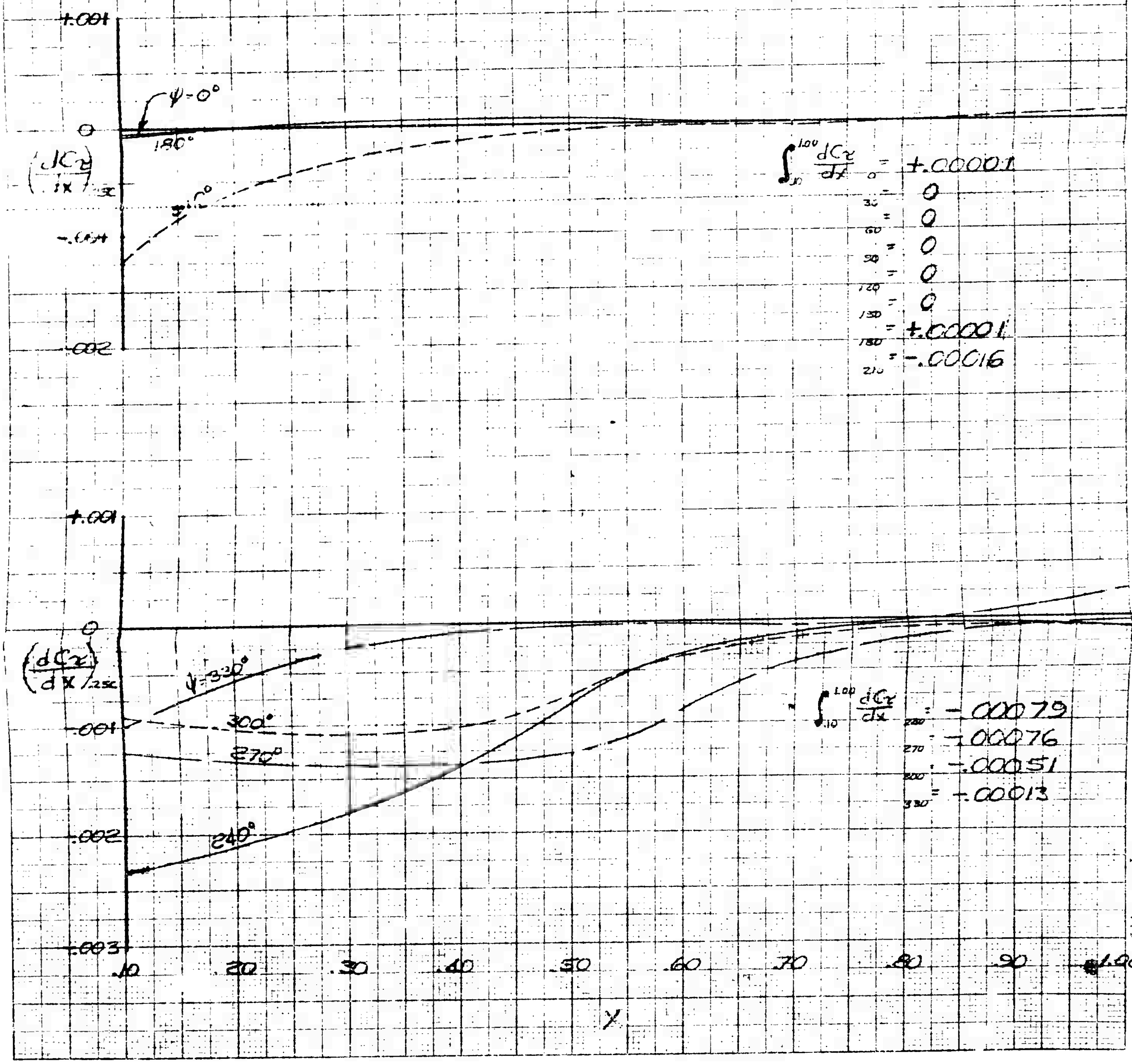


FIGURE 30
TORSION DISTRIBUTION
AUTOROTATION
$\mu = 0.9$
$\theta = 0°$



10 × 10 to the ½ inch, 5th lines accented
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FIGURE 31

TORSION DISTRIBUTION
AUTOROTATION
$\mu = 1.20$
$\alpha = 0°$

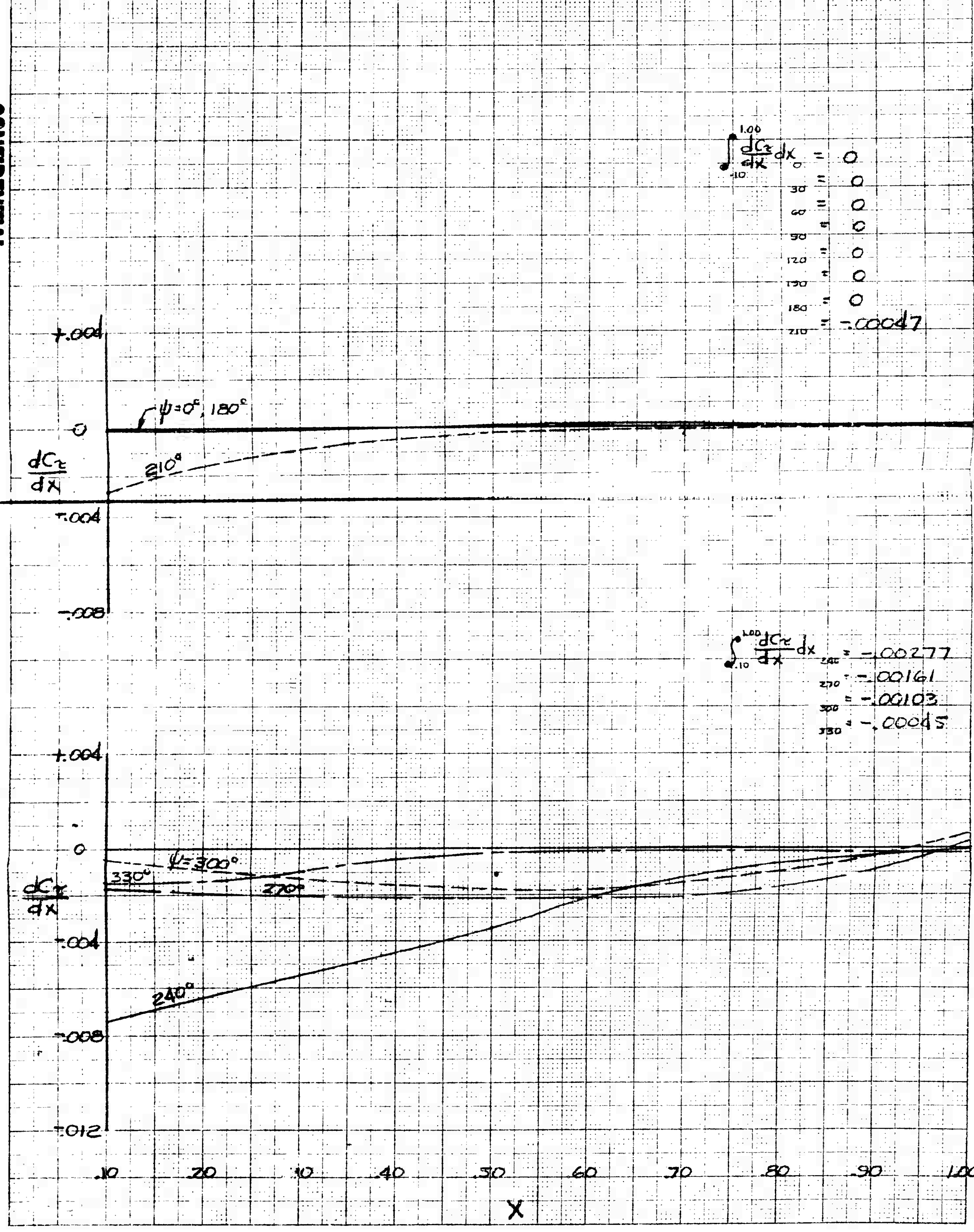

FIGURE 32
TORSION DISTRIBUTION
AUTOROTATION
$\mu = 1.5$
$\theta = 0^\circ$

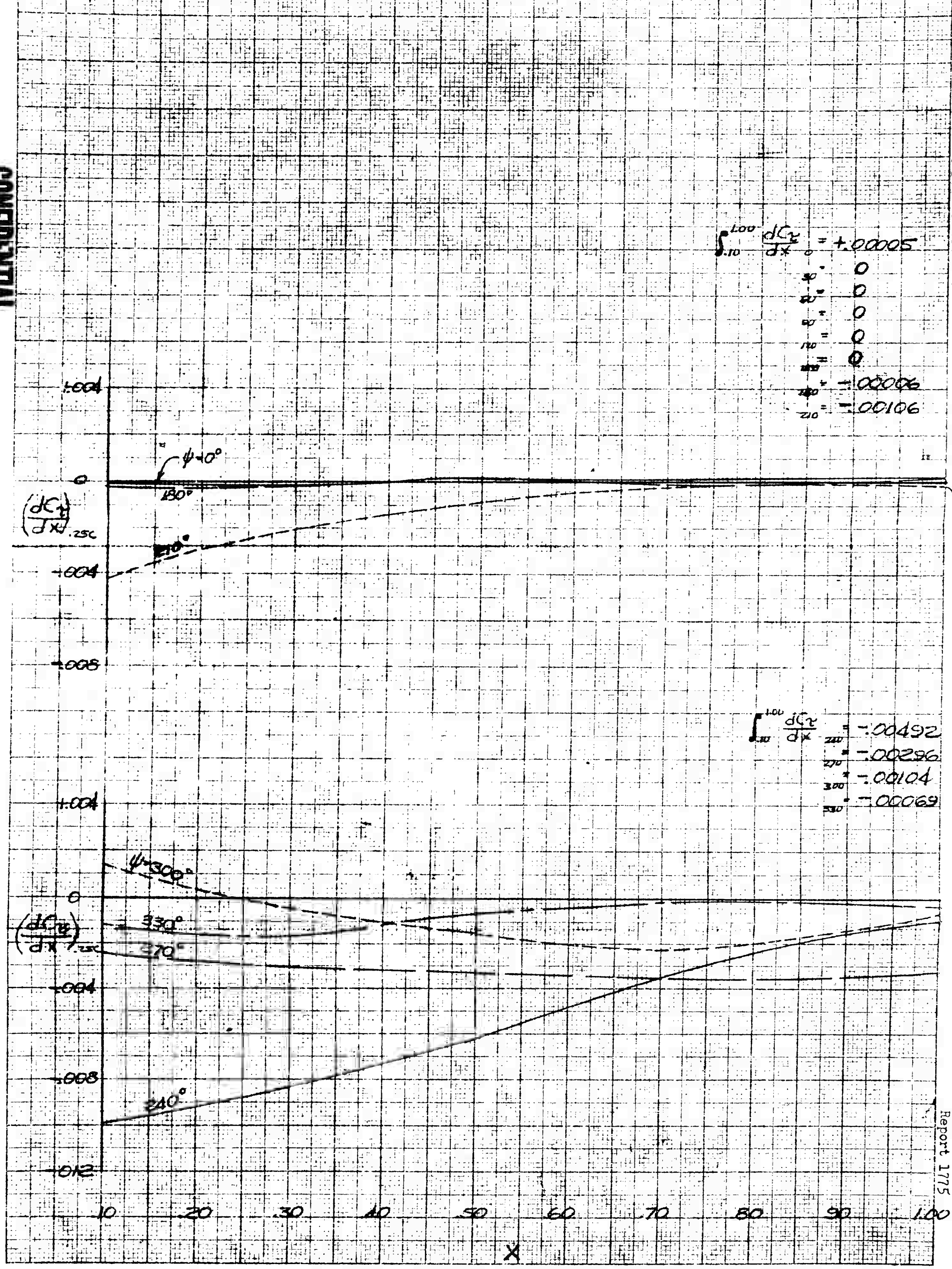

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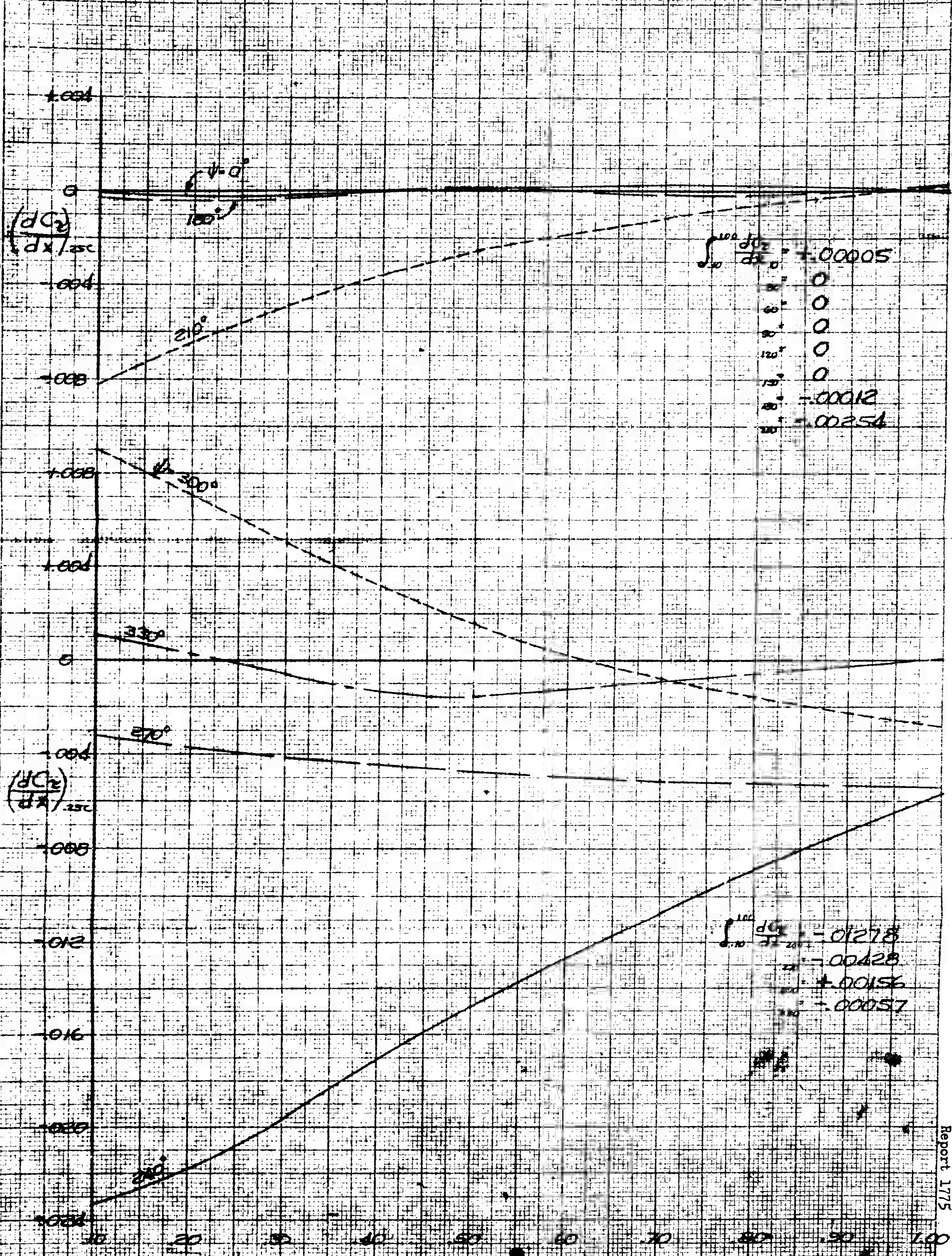
FIGURE 33

TORSION DISTRIBUTION

AUTOROTATION

$\mu = .30$

$\delta = 0°$



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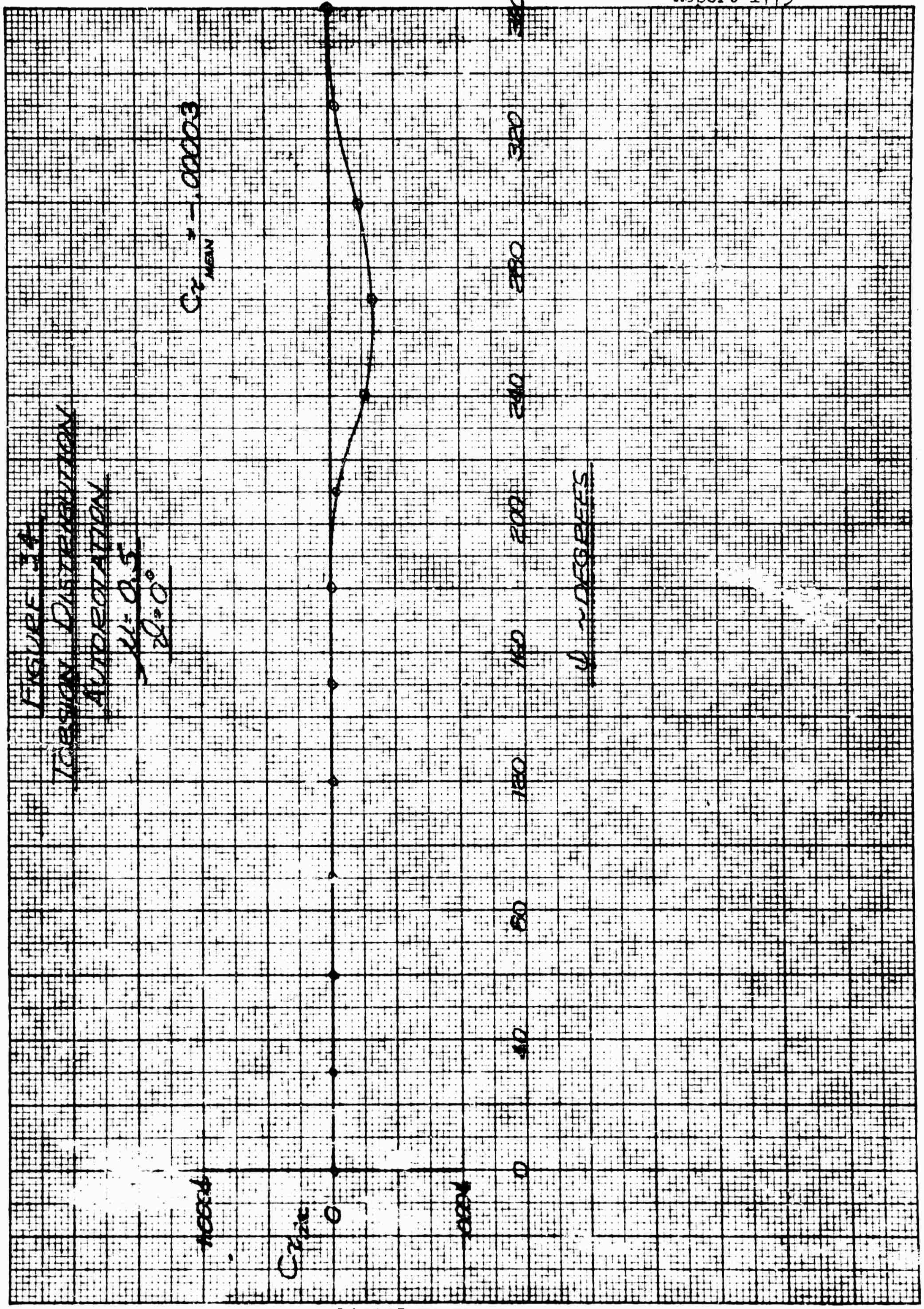

KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 × 10 to the ½ inch, 5th lines accented.
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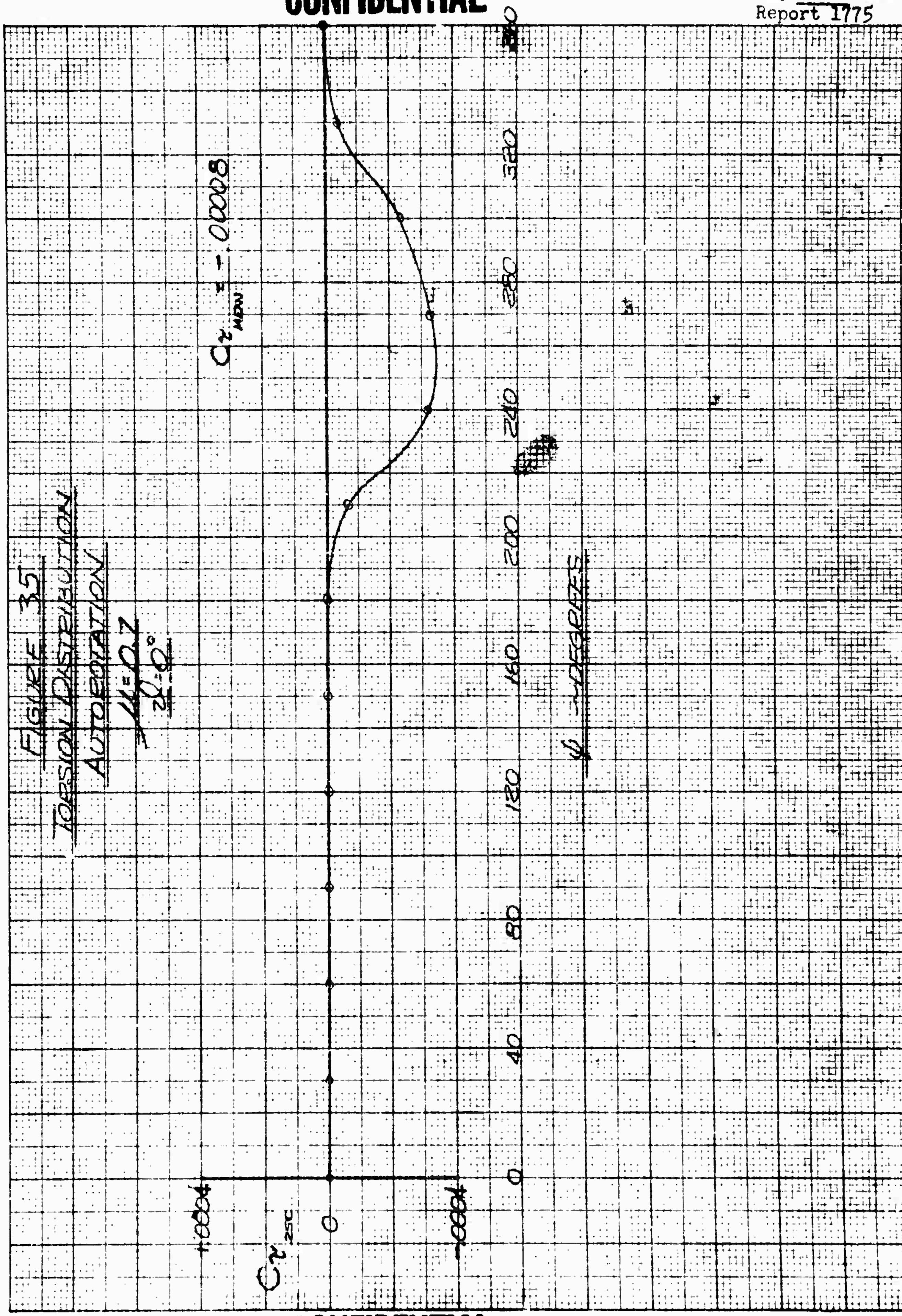
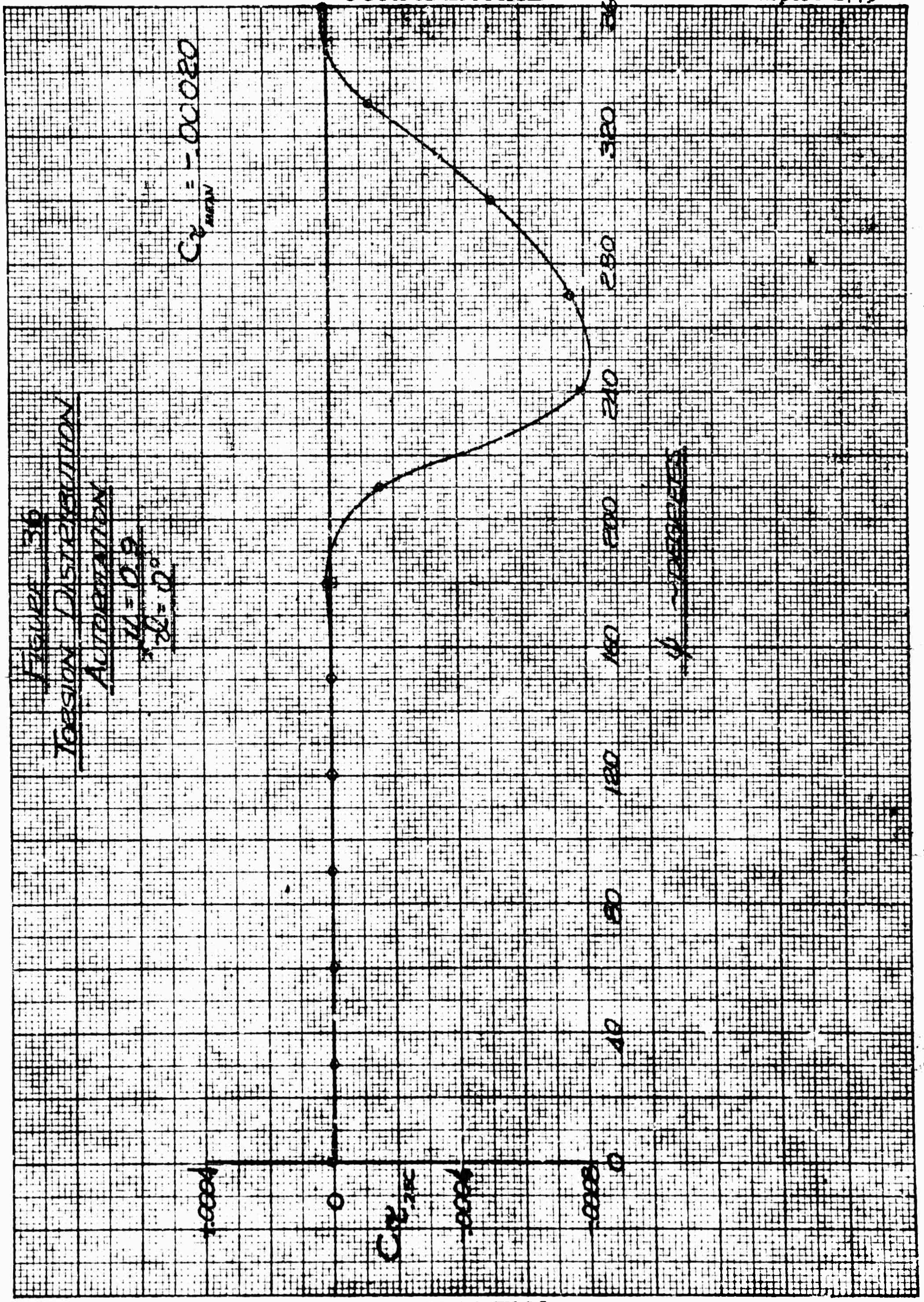


FIGURE 35
TORSION DISTRIBUTION
AUTOROTATION
μ = 0.7
$\alpha_2 = 0°$
$C_{\tau_{MEAN}} = -.00008$
$C_{\tau_{25C}}$
+.0004
0
-.0004
0
40
80
120
160
200
240
280
320
360
ψ ~ DEGREES



KEUFFEL & ESSER CO., N. Y. NO. 359-11
10 X 10 to the ½ inch, 5th lines accented.
MADE IN U.S.A.

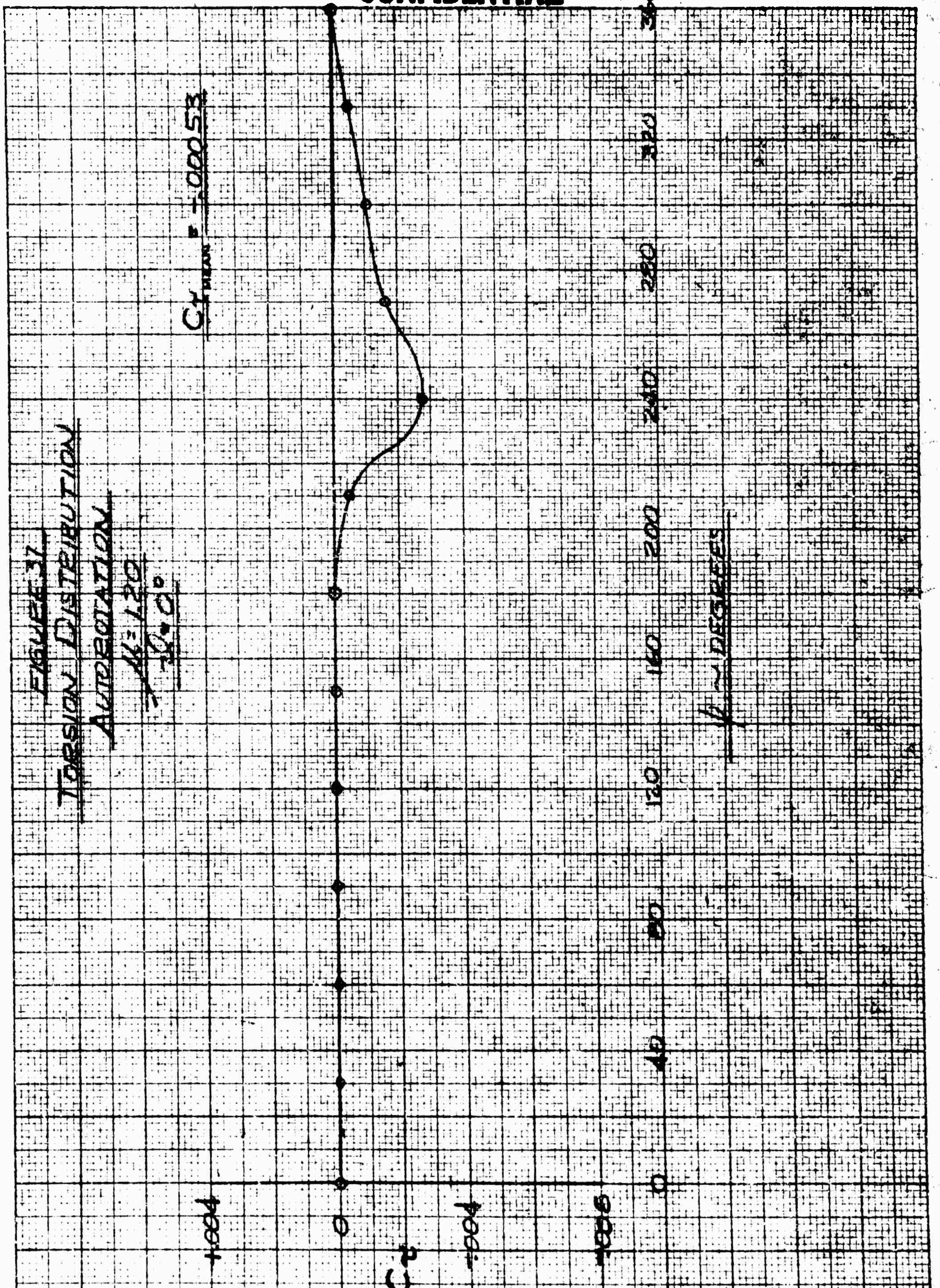


FIGURE 37
TORSION DISTRIBUTION
AUTOROTATION
μ=.120
$C_{t_{MEAN}}$ = -.00053
ψ ~ DEGREES
0
40
80
120
160
200
240
280
320
360
+.004
0
-.004
-.008
C_t

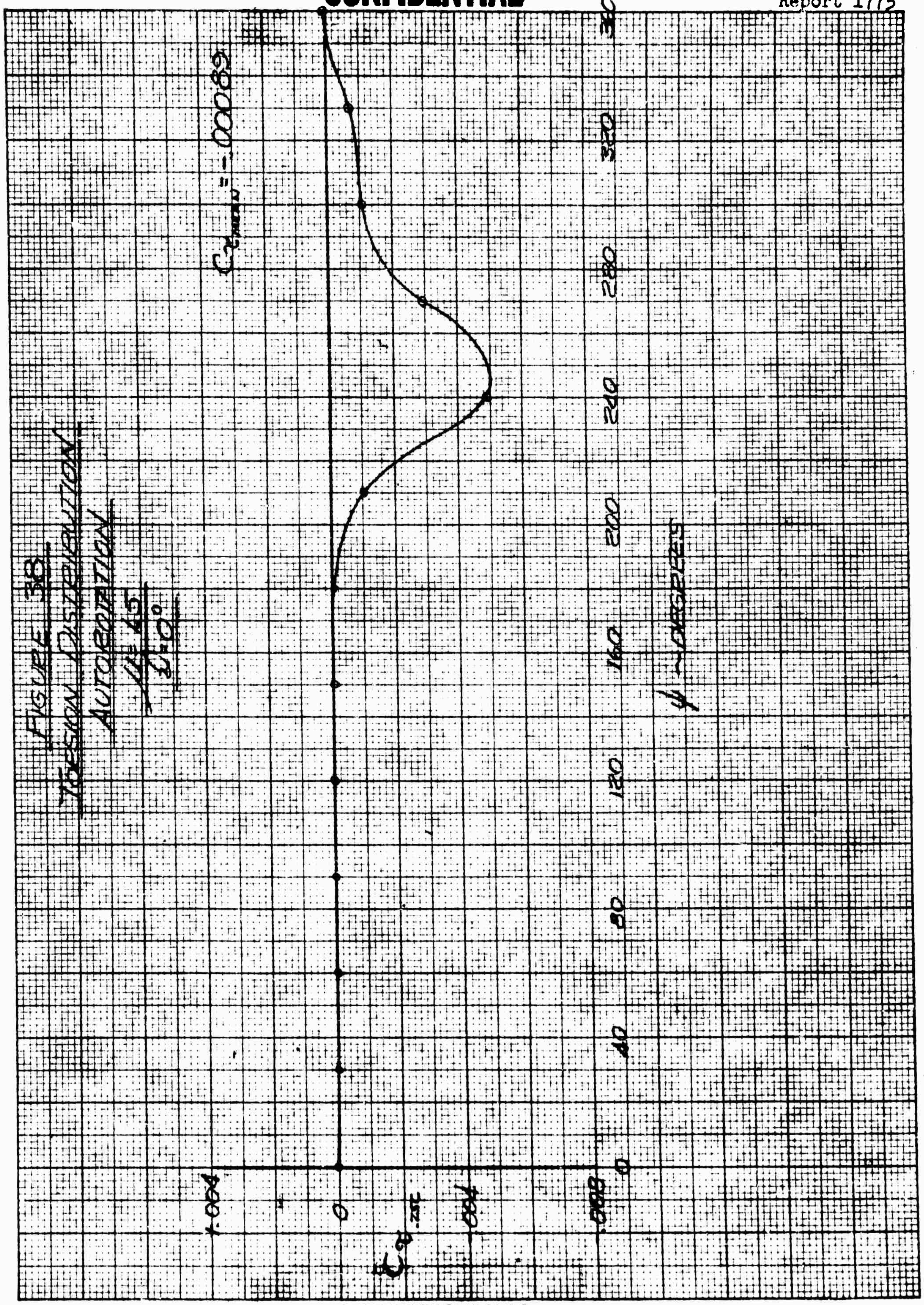


FIGURE 38
TORSION DISTRIBUTION
AUTOROTATION
μ=.45
α=0°
ψ ~ DEGREES
0
40
80
120
160
200
240
280
320
360
+.004
0
-.004
-.008

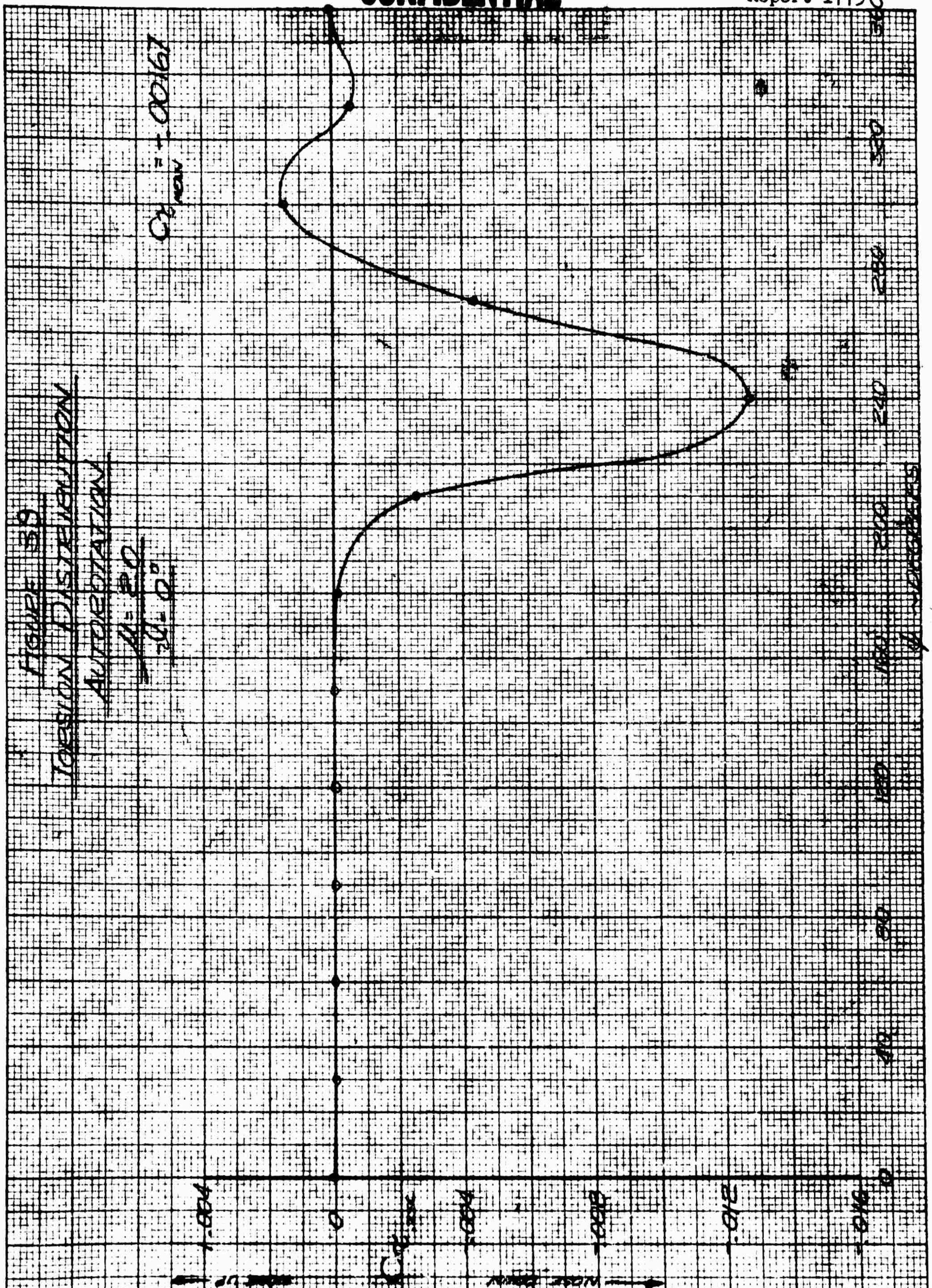


FIGURE 39
TORSION DISTRIBUTION
AUTOROTATION
μ = .20
α = 0°
0
40
80
120
160
200
240
280
320
360
ψ ~ DEGREES
.004
0
.004
.008
.012
.016
NOSE UP
NOSE DOWN

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